CRANFIELD UNIVERSITY

Ross Tierney

The Potential of Reverse Innovation to Improve Urban Toilets

Centre for Competitive Creative Design

PhD
2014 - 2017

Supervisor: Dr. Leon Williams
Associate Supervisor: Dr. Jeff Rao
December 2017

CRANFIELD UNIVERSITY

School of Water, Energy and the Environment

PhD

Academic Years 2014 - 2017

Ross Tierney

The Potential of Reverse Innovation to Improve Urban Toilets

Supervisor: Dr. Leon Williams
Associate Supervisor: Dr. Jeff Rao
December 2017

ABSTRACT

The lack of desirable, waterless toilet options in urban environments around the world leads to major issues that will continue to get worse as population density increases. At the bottom of the economic pyramid, 2.3 billion people lack access to adequate sanitation accelerating the spread of disease through contaminated water and leading to the deaths of over a million children per year. At the top of the economic pyramid, the ubiquitous flushing toilet uses nine litres of water per flush, equating to the average person using 15,000 litres of water per year. As clean water becomes a scarcer resource, wasting and polluting water has to be avoided. Developing new water-saving, desirable toilets to provide a pleasant user experience will increase the likelihood of adoption of more sustainable options. Defecation is a basic human function but also a universal cause for embarrassment and disgust. As the repulsion is visceral and 'hard-wired' human behaviour, many of the same issues arise whether the user is in the poorest slum or a modern apartment building. Designing new products for low income countries that find a secondary market in a high income country is an approach called reverse innovation and has a proven record of producing disruptive innovations by working to strict requirements. This research discusses how reverse innovation has potential to address the challenges and issues associated with low-water sanitation to increase adoption of more sustainable technology. To achieve this, an understanding was gained of the user experience of different low-water toilets through literature review and an ethnographic study in Kumasi, Ghana. A new waterless toilet technology was then developed and tested, primarily targeting the residents of Kumasi before being tested with a secondary target market in the United Kingdom. There were a number of similarities across both target markets, confirming the importance of user experience. The technology was positively received and compatible with user behaviour in the secondary target market indicating the technology could be transferred and an example of reverse innovation. This research intends to encourage and inspire innovation in a sector that effects everyone in the world yet remains an ignored and embarrassing subject.

Key Words: Product development, Sanitation, Reverse innovation, Design for Developing Countries, Urban Sustainability

ACKNOWLEDGEMENTS

I would like to thank the following people:

My supervisors. Leon for giving me this opportunity and his incredible commitment, encouragement and dedication. Jeff for his material expertise and academic guidance. The research sponsor: The Bill and Melinda Gates Foundation for instigating this amazing project that I have been so privileged to be a part of. I have really admired their approach to this challenge by the foundation and Carl Hensman has been a great driving force.

I have been lucky enough to work with a number of great people on this project. I'd especially like to thank Alison and Ewan for always being so generous with their time even from my first week on the project and always great to have a chat with. Sean for being probably the nicest person on campus. Athanasios for his always excellent feedback and his guidance during the reviews. Keith Goffin for his time and wisdom before and after the research trip. Matt Collins who has truly inspired me with his design skills and knowledge. His work on the toilet has been incredible. Edwina for being my testing buddy. Peter for leading the way with the early testing. Jan for the photos and picking up the toilet baton with such enthusiasm! I wish him all the success for his PhD and his future eco-farm. Dr. Yasser Bhatti, Dr. Matt Harris and Dr. Matt Prime for inviting me to Imperial and for the fascinating discussions. The Eco-community at Transition Heathrow for taking part in the research. All of the C4D student and staff throughout the years, to pick a few- Fiona, Bhavin, Kostas, Laura, Jim Hurley. The Mexicans! Jay for all the fun times and motivating chats. Tariq the true champion of C4D. Bernardo – yes… It's finished. The Ethno team were brilliant and so kind to I give up their time to eat pizza and watch people talk about toilets. I miss you all. Nick Jones and bar-barans. Phil jones for the proof reading. The chaps. Astej, I owe you mate. coyw! Brad for making the sacrifice. Eddy for being a great wordsmith, Teresa for keeping me on track. Craig for the hook-up. Mik for inspiring my career choice. Nick Hall for also guiding me in this direction. Fitz for being a damn good motivating voice when I needed it. Andrew for being the best Dave and giving me something to aim for. I owe a huge amount to Jake. A great house mate, car mate, work mate, tea mate, mate. One of the smartest people I know who will have a pretty big impact on the world. Zoe who has picked me up in my low points and made my high points even better. I really couldn’t have got to this stage without her and it certainly wouldn’t have been as enjoyable. She’s really been an absolute star. Jem for being far too good to me for all these years. She’s officially the favourite. My little mum who is just amazing. Her proof-reading, counselling and motivation have integral. And finally, the world’s best dad, who taught me that ‘up there is for thinking down there is for dancing’.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

DISCLAIMER

Describing countries as ‘developing’, ‘developed’ or ‘industrialised’ is intended for convenience and do not express a judgement about the country or region.

All research documented in this thesis was approved by Cranfield University Health Research Ethics Committee (CUHREC).

LIST OF ABBREVIATIONS

ABS	Acrylonitrile Butadiene Styrene
BoP	Bottom of the Pyramid
BMGF	Bill and Melinda Gates Foundation
BSC	Bristol Stool Chart
CEO	Chief Executive Officer
COSHH	Control Of Substances Hazardous to Health
CLTS	Community Lead Total Sanitation
CRI	Coincidental Reverse Innovation
CUHREC	Cranfield University Health Research Ethics Committee
EAWAG	Eidgenössische Anstalt für Wasserversorgung, Abwasserreinigung und Gewässerschutz
FDM	Fused Deposition Modelling
GE	General Electric
GRIT	Global Research Innovation and Technology
IBM-WASH	Integrated Behaviour Model – Water, Sanitation and Hygiene
IRI	Inductive Reverse Innovation
JMP	Joint Monitoring
LFC	Leverage Freedom Chair
LGT	Local Growth Team
MaP	Maximum Performance
MBR	Membrane Bio-Reactor
MDG	Millennium Development Goal
MNC	Multi-National Corporation
MIT	Massachusetts Institute of Technology
NMT	Nano Membrane Toilet
OD	Open Defecation
P1	Prototype 1
P2	Prototype 2
P3	Prototype 3
PSI	Pneumatic Solutions International
PTFE	Polytetrafluoroethylene
RTTC	Reinvent the Toilet Challenge
RWF	Rotating Waterless Flush
SDG	Sustainable Development Goal

SLIPS	Slippery Liquid Infused Porous Surface
SOIL	Sustainable Organic Integrated Livelihoods
SLS	Selective Laser Sintering
SMEs	Small and Medium Enterprises
ToP	Top of the Pyramid
UDDT	Urine Diverting Dry Toilet
UN	United Nations
UNHCR	United Nations High Commission for Refugees
UV	Ultraviolet
VOC	Volatile Organic Compounds
W.C	Water Closet
WEDC	Water Engineering and Development Centre
WSUP	World Sanitation for the Urban Poor

"You never change things by fighting the existing reality. To change something, build a new model that makes the existing model obsolete."

R. Buckminster Fuller (date unknown)

1 INTRODUCTION

This chapter begins with outlining the key motivators for the thesis, from both a research perspective and a personal perspective. The concept of 'reverse innovation' is then introduced with a brief overview. The upcoming chapters are summarised for ease of navigation for the reader. The three main stages of the Introduction are shown in Figure 1. Each chapter in the thesis will follow the same format of selecting three key stages and stating what the stage is comprised of and the purpose.

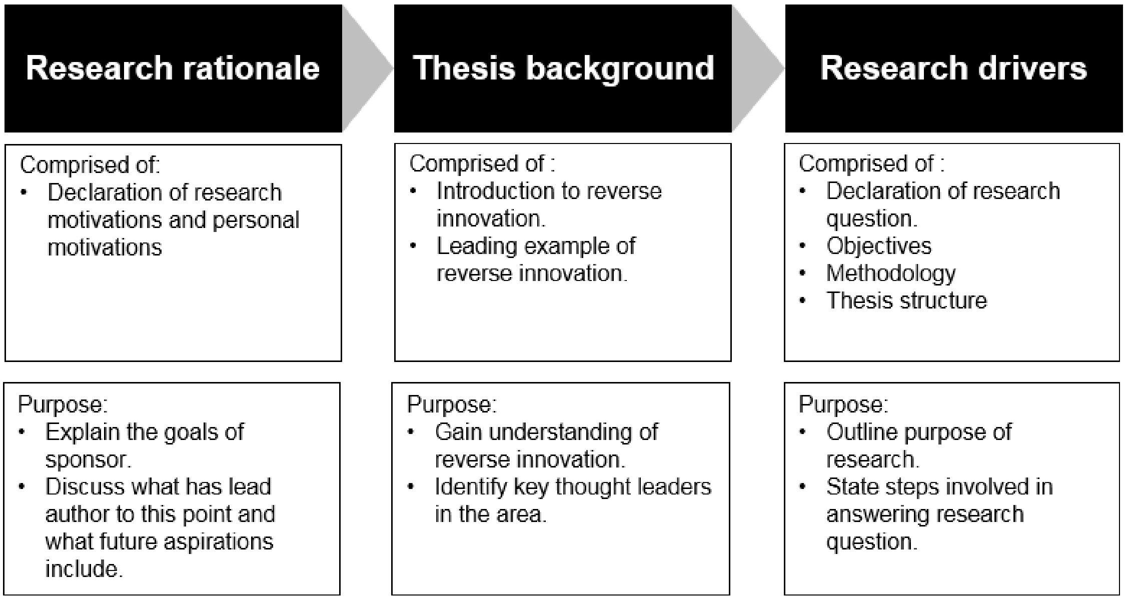


Figure 1 - Diagram of chapter structure, content and rationale.

1.1 Personal motivation

From a young age I have loved drawing and building and I became very good at art and design leading me to study Product Design as my undergraduate degree. I began to think about design as a way to solve problems and not just make objects more desirable. I remember thinking that there are enough chairs in the world, you're probably sat on one now, that do the job fine, but solving a real world problem with an elegant solution will always be an exciting challenge. For my final major project I designed a smokeless stove for developing countries inspired by a TED talk on the subject by Amy Smith of MIT. I almost didn't choose it as a project because it seemed too daunting a task but my very inspiring tutor, bluntly stated if I'm "not aiming for the big problems of the world, there's no point being here". He was right. After finishing my degree, I worked for free designing other low cost products for a company in Kenya before joining a charity called Child Reach International in Moshi, Tanzania. I designed a new low-cost smokeless stove for the region and then worked with the local team to teach teenagers in the surrounding villages how to make it as part of a small sustainable business.

Upon return to the UK, I was recommended to apply for a Masters by Research at Cranfield University working on the design of the Nano Membrane Toilet by a former lecturer. After a year of hard work, I was part of the team presenting the project in India to the Bill and Melinda Gates Foundation and we progressed to the next phase allowing me to pursue a PhD. As my research into low-water sanitation for developing countries has progressed, I became more interested in how the new technology could also be of value to the rest of the world. As more people move out of poverty and the worldwide urban population continues to increase, we will need to develop new technology to remove excreta safely without using nine litres of water per-use like flushing toilets in a way that's pleasant for the user. This project has been an incredible honour to be a part of and has given me amazing experiences and the chance to meet and work with truly inspiring people. Getting to travel to interesting and new places will forever be one of my greatest passions and I still love drawing and building. These passions undoubtedly contribute to why I love the career I have chosen but the idea that something I have worked on could improve the lives of people in developing countries is the dream I'm working towards.

1.2 Research motivation

In developing countries around the world, urban sanitation often has poor user-experience as well as being a cause of disease and risk of attack particularly for females (Satterthwaite and Mcgranahan, 2006). The desirable flushing toilets, that are used by the world's wealthier people use approximately nine litres of water per use, an unsustainable amount as the world's population continues to increase (Esrey et al., 2001). More innovation is needed at the Bottom of the Pyramid (BOP) to improve the poor user-experiences linked with toilet use. Flushing toilets have changed little since 1775 and also need improvement to reduce the huge impact on the environment (Elledge and Mcclatchey, 2013). Urban environments in developing countries can be characterised by insufficient infrastructure and dense populations, magnifying the issues with sanitation far more than in rural areas where populations are more dispersed (McGranahan, 2001). As 2.5 billion people will be added to the world's urban populations by 2050, with close to 90 percent of the increase concentrated in Asia and Africa (UN, 2014), desirable sanitation options are needed without causing further impact to the environment.

This research was funded by the Bill and Melinda Gates Foundation (BMGF) as part of the Reinvent the Toilet Challenge (RTTC). The RTTC was initiated in 2013 with the aim to develop sanitation solutions for the 2.6 billion people lacking adequate sanitation. Poor sanitation leads to the death of almost two million children annually (Thomas, 2015). The full goals of the challenge can be found in Figure 2. The Nano Membrane Toilet (NMT) developed by Cranfield University, was one of the successful teams to be awarded funding to pursue the research further. The author of this thesis was a member of the design team, whose role was to ensure a good user experience was considered throughout the design process into the final toilet solution.

The Reinvent the Toilet Challenge aims to achieve the following goals:
• Address the failures of the 18th-century toilet, which is not meeting the current needs of 2.6 billion people who lack access to sanitation
• Devote funding and attention to the need for a new toilet
• Generate innovation among a wider research and development community
• Support upstream research and development of a toilet that:
» Is hygienic and sustainable for the world's poorest populations
» Has an operational cost of $0.05 per user, per day
» Does not discharge pollutants, but instead generates energy and recovers salt, water and other nutrients
» Is designed for use in a single family home
• Create a toilet that does not rely on water to flush waste or a septic system to process and store waste
• Create a toilet that is the basis for a sanitation business that can be easily adopted by local entrepreneurs living in poor urban settings
• Raise awareness about this research by publishing scientific papers in journals and articles in various media outlet

Figure 2 – Goals of the Reinvent the Toilet Challenge funded by The Bill and Melinda Gates Foundation (Kone, 2012)

Another of the organisations involved in the RTTC was the Swiss Water research institution, Eidgenössische Anstalt für Wasserversorgung, Abwasserreinigung und Gewässerschutz (EAWAG). The design of the EAWAG toilet was conducted by the design firm Eoos and the toilet system they developed was called the Blue Diversion Toilet. Eoos practiced 'co-design' with residents in Kampala, Uganda to ensure the system is appropriate for the target market (Figure 3). Although co-design is a well-known method in product development, the process can be resource intensive and challenging, especially if the target market is in a different country (B-N Sanders & Jan Stappers, P. 2008). Due to resource constraints, the design team at Cranfield University did not partake in co-design and instead focussed on User centred design informed by primary research in the target market.

Figure 3 - Designers from Eoos taking part in a co-design workshop in Uganda (Eawag 2014)

Deep understanding of a target market is essential for product development but literature on user behaviour in sanitation is sparse. Existing literature has mainly focussed on the processing of excreta with the user experience largely overlooked (Katukiza et al., 2010a). An understanding of the non-technical issues is fundamental to the acceptance and sustained use of implemented technologies (Roma et al., 2010). User experience is also rarely mentioned in policy and planning as a way to improve sanitation (Black and Fawcett, 2008). Projects with the goal of supplying clean water will often use technical approaches to solve the technical problem of ensuring the delivery of clean water. Supplying sanitation requires a softer, people based approach to ensure success (Satterthwaite and

Mcgranahan, 2006). For example, Community Lead Total Sanitation (CLTS) is a 'soft' method primarily used in rural communities to end open defecation by employing social change and community pride (Myers, Cavill and Pasteur, 2016). Community sessions are held so inhabitants realise that open defecation in the community impacts everyone and this 'triggers' the community members to eschew the practice in future and invest in pit latrines. The community drives the action from that point on, ensuring a high success rate (Curtis, 2016). Once there is the demand for the toilet, a suitable technology will have to be available that is within the means of the user and suitable for the context (Coombes, 2016). Simple technology that users can instantly see the benefits of, will be more likely to be adopted (Rogers, 2010). A good example of how the behaviour change techniques are complemented by simple technology is the *'Tippy Tap*'. The first step is users becoming aware of the need to wash their hands after using the toilet, then a simple water pouring device is constructed outside of the latrine with easily sourced objects[1]. The user steps on the pedal on the floor, tipping the water container forward pouring water to wash the hands as shown in Figure 4. The pedal action is more hygienic as the user doesn't have to touch anything by hand contaminating any surfaces (Devine, 2010). Understanding the user was the crucial first step in both of these successful examples of improving sanitation.

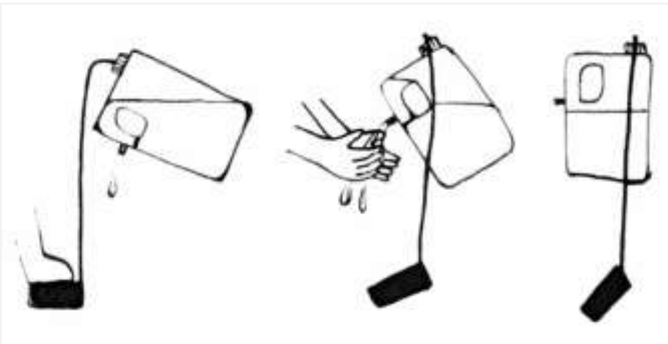


Figure 4 - Diagram of the Tippy Tap in use for washing hands after using the toilet (Danielsson, 2012)

[1] Tippy Taps can be made from a piece of string, a water container and something to support the container and allow it to be tipped to pour water

Designing products for the BOP should not just be seen as a 'moral' thing for a company to do but also for huge, underserved market opportunity. As the combined buying power of the four billion people living in the BoP is $5 trillion (Karamchandani, Kubzansky and Lalwani, 2011) there can be reward for the risk taken targeting this underserved group. Prahalad (2005) describes in the seminal book *'Fortune at the Bottom of the Pyramid'*, "If we stop thinking of the poor as a burden and start recognizing them as resilient and creative entrepreneurs and value-conscious consumers, a whole new world of opportunity can open up". Govindarajan (2013) builds on this idea, describing how "reverse innovation" can lead to new disruptive products for the developed world that would not have been produced following standard, incremental design improvements (Govindarajan and Ramamurti, 2011). As there is a great need for innovation within sanitation at the bottom of the pyramid, and the market at the top of the pyramid has stagnated, there is potential that reverse innovation could be the ideal strategy to maximise impact.

> *"Affordability is an important issue because people don't have the same income as people in rich countries. But reverse innovation is not about hitting low price points; it is about creating fundamentally different products to meet the needs of people in these markets. People at the middle of the pyramid don't necessarily want low-price products; what they want is products that meet their needs"* (Govindarajan and Euchner, 2012).

A well-known, macabre quote states; "One death is a tragedy. One million deaths is a statistic"[2] when discussing numbers as huge as the sanitation crisis (such as causing almost two million childhood deaths per year (Thomas, 2015)) it is difficult to truly grasp the size of the problem. The concept is too large to easily comprehend. This project intended to shift the focus of issue on to the people that the situation effects. A deeper understanding of the needs of the end user is required to ensure an effective solution can be developed. Furthermore, there is

[2] This is often attributed to Josef Stalin but there is no clear evidence he said it (Exenberger and Hamilton, 2009)

a need to explore the potential of reverse innovation for achieving improved toilet solutions that people around the world want to use, not just have to use.

1.3 Research background: Reverse innovation

Reverse innovation' refers to the case of an innovation being first adopted in the developing world before 'trickling up' to markets in the developed world (Govindarajan and Ramamurti, 2011). This concept is potentially applicable and important to the case study, the Nano Membrane Toilet. The household, waterless toilet system is currently being designed for developing countries to prevent the spread of waterborne disease. There is also potential value to reach unmet needs in the developed world. Reverse innovation was first coined in 2009 by Jeffrey Immelt and Vijay Govindarajan in an article declaring General Electric's new strategy. Conventional Innovation targets the world's richest people then filters down; Reverse Innovation targets the people at the bottom of the pyramid and then later serves unmet needs in the developed world. Govindarajan goes into more detail in his book titled *'Reverse Innovation: create far from home, win everywhere'* and explains how the existing strategy to tap into the emerging markets is not working. 'Glocalization' is the name given to the long practiced method where companies export lightly modified versions of existing products, mainly the basic versions with fewer features (Govindarajan and Trimble, 2013). In the BoP Protocol (Simanis and Hart, 2008) the authors argue that the Glocalization approach may produce incremental sales in the near term but will almost always fail in the long term. Both of these texts refer to the great potential being missed and also the potential risk to the long-term strategy of a multinational corporation. It is suggested that established western MNC's can be surpassed by a company that started in a developing country and fulfilled the needs of the huge population and continued to expand. Govindarajan's first article was co-written by Jeffrey Immelt, the former CEO of GE who has also promoted the benefits to reverse innovation over glocalization. In the article, the authors state potential great risk that comes from emerging brands over existing rivals.

"If GE doesn't come up with innovations in poor countries and take them global, new competitors from the developing world-like Mindray, Suzlon, Goldwind, and Haier-will. That's a bracing prospect. GE has tremendous respect for traditional rivals like Siemens, Philips, and Rolls-Royce. But it knows how to compete with them. They will never destroy GE. By introducing products that create a new price-performance paradigm, however, the emerging giants very well could." (Immelt, Govindarajan and Trimble, 2009).

Govindarajan and Ramamurti declare five reasons why innovations may 'trickle-up' from poor to rich countries:

- Innovations developed in developing countries may have a ready market among poor people in rich countries.
- Dramatic cost and price reductions of 70 to 90 percent achieved to succeed in developing countries can help expand demand in developed countries.
- New features incorporated for developing countries, such as sturdiness, profitability, or ease of use, may create new market segments in rich countries.
- Technology of 'good enough' products developed for developing countries may improve over time to satisfy high-end applications in rich countries.
- Developing countries may leapfrog to latest technologies, especially if they have a large internal demand, are unencumbered by legacy technologies, and face fewer regulatory obstacles. (Govindarajan and Ramamurti, 2011)

The final reason could be of relevance to sanitation. Toilets have changed little in the past two centuries (George, 2008) and could be an industry in need of disruption. In the first systematic literature review of reverse innovation, Hadengue *et al.* (2017) profiles 66 examples of reverse innovations ranging from the Leverage Freedom Chair (LFC) to a handheld Electrocardiogram General Electric (Hadengue, De Marcellis-Warin and Warin, 2017). There are no examples given of products related to sanitation in the list.

1.3.1 Leading examples of reverse innovation

A recent design project by a team at Massachusetts Institute of Technology (MIT) that has proven to be a successful example of reverse innovation is an all-terrain wheelchair. The Leverage Freedom Chair (LFC) has an innovative lever mechanism that allowed for easier ascent up hill and traversing rough terrain. The cost per chair was $200 which is within the $150 to $300 of other locally made wheelchairs (Winter et al., 2009).

Figure 5 - Photos of a reverse innovation example; (A) The Leverage Freedom Wheelchair (LFC) designed for India and (B) the redesigned wheelchair for secondary target market, off-road wheelchair users in developed countries (Judge, Hölttä-Otto and Winter, 2015).

The improved design was admired by 'off-road' wheelchair users in the United States of America that currently use very expensive high-tech wheelchairs. The LFC was redesigned for the secondary target market costing $3,300 which is significantly more expensive than the LFC but between 40% and 67% the price of other off-road wheel chairs (Winter et al., 2013). Reverse innovation has not been thoroughly explored in relation to sanitation solutions before this research. The LFC was designed to meet the harsh environment need for easy construction and maintenance.

Another well-publicised examples of reverse innovation is the portable electrocardiogram machine by General Electric (GE). Electrocardiograms (ECG) are non-invasive, risk-free tests that measure electrical activity in a patient's heart. The tests themselves are low-cost but the machine would normally be prohibitively expensive to all but hospitals in major urban centres in developing countries. The weight and power requirements of the equipment also made the current ECG machines unfeasible in rural India where the test is widely performed (Govindarajan and Trimble, 2013). A redesign of the ECG machine (Figure 6) to meet the harsh requirements for rural China produced a handheld, battery powered device that was portable and cost one-third the price of rival technology. The simple interface ensured easy use based on core functions.

Figure 6 - (A) GE standard ECG machine (B) ECG redesigned for use in rural China

Hadengue's 2017 article reviewed 51 reverse innovations detailing the locations that are key to determining whether the innovation is a conventional or reverse innovation, five of the technologies that feature in this thesis are have been extracted from Hadengue's article and shown in Table 1.

Table 1 - Five example products from the table published in the Hadengue, M. *et al.* (2017) systematic literature review

Company from developed country	Headquarter location	Reverse innovation product	Concept idea location	Development location	Primary market	Secondary market	Type of Reverse innovation	Paper(s) mentioning the product
Deere & Company (John Deere)	Moline, US	Krish tractor	India	India	India	Worldwide	Strong	Govindarajan and Trimble (2012) Govindarajan and Euchner (2012)
General Electric Healthcare	Little Chalfont, UK	Portable ultrasound device.	China	China	China	USA	Strong	Immelt *et al.* (2009), Talaga (2010), Armanios and Li (2013), Brem and Ivens (2013).
GRIT (Global Research Innovation and Technology)	Cambridge, US	Leverage Freedom Chair (LFC)	USA	USA	India/ Guatemala	USA	Weak	Judge *et al.* (2015)
Harman	Stanford, US	SARAS	USA	China/India	China/India	Japan	Strong	Govindarajan and Trimble (2012)
Nokia	Espoo, Finland	"Mass-entry market" phones	Finland	China	China	Europe	Strong	Govindarajan and Ramamurti (2011) and von Zedwitz *et al.* (2015)

Hadengue also states the following in the review which is of particular interest to this thesis. *“Reverse innovation has mainly been example driven and there has yet to be established practice of reverse innovation in a specific industry. Doing so would allow for a more in depth study of the phenomenon”* (Hadengue, De Marcellis-Warin and Warin, 2017). This research will investigate the opportunity for reverse innovation to improve sanitation with a focus on urban environments. Urban communities were identified as the issues associated with poor sanitation are magnified when areas are more densely populated (UN-HABITAT, 2007).

1.4 Study Aim, Objectives and Research Question

The aim of this research is to improve the understanding of the issues associated with sanitation and inspire innovation in a sector that affects everyone. Through early scoping, reverse innovation emerged as an approach that has potential to improve sanitation for everyone. As a result of the goals of the sponsor (The Bill and Melinda Gates Foundation), the study aim and scoping of innovation in developing countries, the research question is:

How can reverse innovation improve urban sanitation?

1.5 Aim and Objectives

The aim is: Increase adoption of low-water toilets in urban environments.

The objectives are:

- To review literature surrounding low-water sanitation options with a focus on the user experience.
- To identify and analyse the frustrations and perceptions associated with using different toilets by residents in Kumasi, Ghana (the project’s primary target market).
- To develop and test a technology to improve the user experience of a waterless toilet.

- To evaluate the new technology with real users and the potential for waterless sanitation technology to be adopted in a secondary target market.

1.6 Methodology

This thesis will document the opportunity for reverse innovation to improve urban sanitation. Figure 7 depicts the visual methodology of the thesis beginning with Introduction and closing with Conclusion. The main body of the thesis can broadly be divided into two parts. First the exploration of the research problem will be comprised of a literature review on the different waterless technology and primary investigation into toilet users in Kumasi Ghana. The second part involves the development and testing of a new waterless toilet technology, originally designed for the residents of Kumasi, Ghana that could also transfer to a secondary target market. The research is then critically analysed in the discussion.

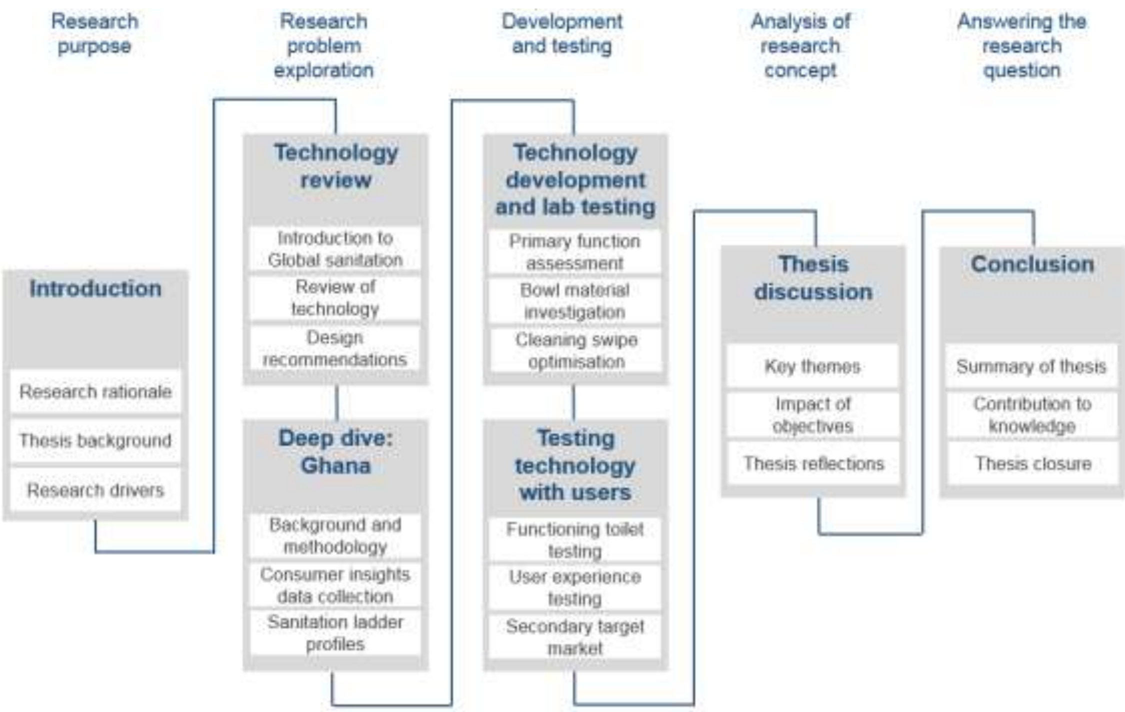


Figure 7 - Visual methodology of thesis (Tierney, R. 2017)

1.7 Thesis structure

Each chapter heading in the thesis is accompanied by a reminder of the corresponding objective and a diagram showing three key stages from the chapter. Each chapter will finish with a closing statement on the key findings of the chapter and the relationship to the following chapter. A brief outline of the chapters and their content is described below to give clarity on the thesis structure:

Chapter 1. Introduction.

The motivations and structure for the research will be presented along with an introduction to the model of reverse innovation and how it has been successfully implemented in different sectors.

Chapter 2. A review of water saving toilets for urban environments.

The review undertaken started with open defecation as the most basic form of defecation then used the structure of Kvarnström's updated sanitation ladder to examine various technologies with a focus on user experience.

Chapter 3. Examining the primary target market: Kumasi, Ghana.

A deeper understanding of target market user attitudes and behaviours was acquired using ethnographic research techniques. Identifying barriers and enablers for adoptions of toilets and frustrations as well as frustrations with current toilet options.

Chapter 4. Development and testing of waterless toilet technology.

The development and testing of a waterless toilet technology is presented from basic concept into testing prototype. Key stages and considerations for developing waterless toilets were identified.

Chapter 5. User testing of a waterless toilet technology.

The newly developed sanitation technology was tested with real users to gain an understanding of user experience. Testing with a secondary target market took place to ascertain acceptance and transferability.

Chapter 6. Discussion

Identify key themes that emerged from each Objective and discuss their individual merit as well as importance to the research question. Utilise multiple sources to solidify value of each theme and ensure rigour.

Chapter 7. Conclusion

Conclude thesis by answering research question. Reflect on complete thesis and limitations as well as opportunities for further research in this area.

1.8 Chapter One highlights

This chapter introduced the research in three areas. The research rationale was presented as ‘research motivations’ (outlining the project goals to build a new waterless toilet) and the ‘personal motivations’ of the author. The research background gave an introduction to reverse innovation, a process that has previously not been thoroughly discussed in relation to sanitation prior to this thesis. The next chapter will review current sanitation technology in use around the world and what are the current issues that need to be addressed.

"First of all - and obviously – having easy access to a toilet constitutes a sine qua non for wellbeing. One cannot feel at ease if one cannot comfortably ease oneself".

Van der Geest (2002)

2 A REVIEW OF WATER-SAVING TOILETS FOR URBAN ENVIRONMENTS

Objective One: *To review literature surrounding low-water sanitation options with a focus on the user experience.*

The various toilet options in use in urban environments around the world are reviewed in this objective, with a focus on the user experience. The health and environmental issues that result from sanitation are also discussed to inform the future of urban toilets. In urban slums of developing countries, pit latrines shared by multiple families are the most common sanitation option. Poor sanitation accelerates the spread of disease through the community whilst also being notoriously unpleasant to use. Meanwhile, in industrialized countries, the desirable 'flush and forget' mentality is enabled by a system that uses around nine litres of clean water per visit, having a significant impact on the environment. By discussing attributes in relation to the user experience it is intended to lead to features that are transferable to improve low-water toilets regardless of the wealth of the target market.

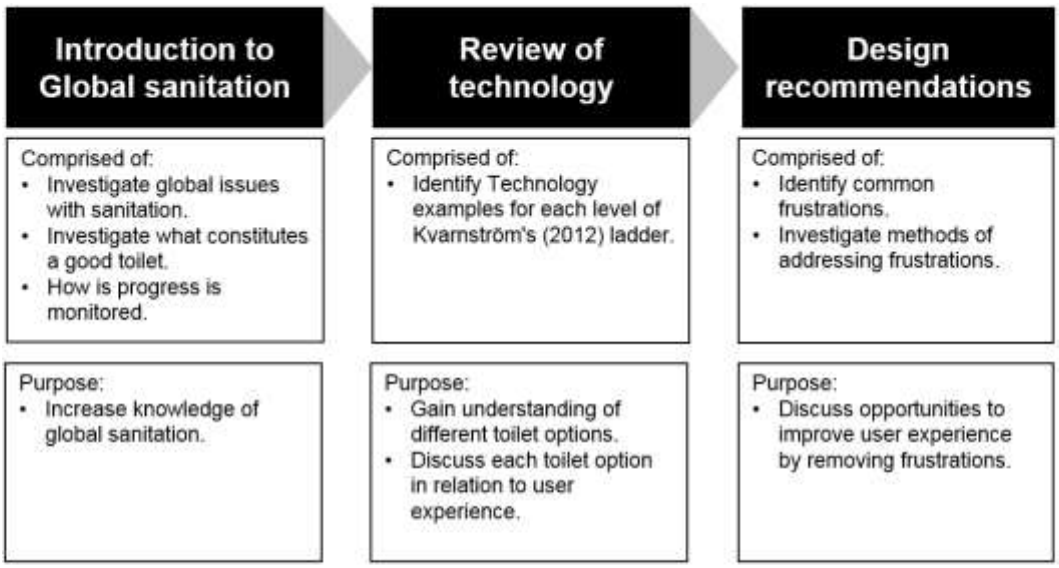


Figure 8 - Chapter structure and rationale of Objective One

2.1 Background information on issues associated with sanitation in urban environments

Innovative low-water sanitation technologies are required at both ends of the economic spectrum in order to sustainably serve the needs of the world's booming population. The average flush of a 'western' toilet is nine litres, meaning each person flushes away 15,000l of clean water per year – thus putting significant strain on water sources and the sewage network of many capital cities (Esrey et al., 2001; George, 2008; Quitzau, 2007). The considerable amounts of water used by flushing toilets can have an unexpected negative effect on aquatic environments (Narain, 2002; Teh, 2013). It is estimated that the number of people living in severely water stressed environments will increase from 1.7 billion in 2003 to 2.7 billion in 2050 and that 5 billion people could be living under at least moderately stressed conditions (Oki, 2003; Schlosser et al., 2014). At the bottom of the economic pyramid there are 2.5 billion people without access to improved sanitation, and in densely populated areas this causes serious health and environmental issues as they use unsafe shared facilities or openly defecate (Katukiza et al., 2010b; WHO, 2009; WHO and UNICEF, 2016). As people in the poorest areas of the world seek to upgrade their sanitation options, they will aspire to own the 'impractical luxury' of a western flushing toilet (Paterson, Mara and Curtis, 2007; Seymour and Hughes, 2014; Sugden, 2014). In 2007 the world's population living in towns and cities surpassed that of rural areas for the first time in human history: the majority being in developing countries where unimproved sanitation is at its most hazardous. This has been identified in the World Health Organization's 2016 Global Report on Urban Health stating, "*Despite significant global progress, lack of access to safe and sustainable water and sanitation continues to pose an urgent challenge for cities*". To address this, one of the 2016 Sustainable Development Goals (SDG) is to ensure water and sanitation needs are met by 2030, when the population is predicted to be 8.5 billion (Moe and Rheingans, 2006; UN, 2016; WHO, 2016).

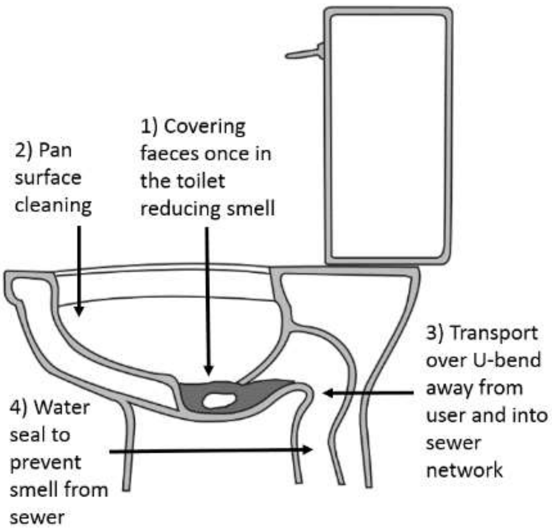


Figure 9 – Role of water within a conventional western toilet (Tierney, R. 2017)

The British Medical Journal named the toilet the greatest medical advance since 1840. However very little innovation takes place in this sector (Fawcett, 2009). This is likely due to sanitation being an unpleasant and taboo subject and – from a user's perspective – the flushing toilet does the job very well. The first major innovation for toilets was the U-bend (also known as the S-Trap) featured on Alexander Cummings patent for a 'valve closet' in 1775 to prevent odour. It has been a standard feature almost ever since but relies on a consistent amount of water to be present (Antoniou et al., 2015; Callow and Patricia, 2012). Bad odour from human waste is a universal trigger for disgust and a major factor for people considering new sanitation solutions (Chappuis et al., 2016; Sato et al., 2002). Jenkins (2007) noted the importance of odour in negative perceptions of current public toilet use in developing countries. In a survey, smell was the most disliked attribute of current defecation places (27.1%) followed by a lack of cleanliness (26.6%). This can be attributed to the sight and/or smell of fresh faeces being perceived as a vector of sickness (Rheinländer, 2013). The transfer of disease through bad odour is a belief that has been seen in many cultures throughout history. Smell – rather than drinking the contaminated water – was frequently blamed for causing Cholera epidemics (Afful, Oduro-Kwarteng and Awuah, 2015; Williams et al., 2010). Additional information on cultural repulsion to faeces can be found in Appendix A.1. The greater risk to health through water source contamination is from faeces rather than urine. One gram of fresh faeces from an infected person can contain around 106 viral pathogens, 106 – 108 bacterial pathogens, 104 protozoan cysts or oocysts and 10-104 helminth eggs (Lim and Vythilingam, 2014; Mara et al., 2010a). There is no data in the literature on the ‘stickiness’ of faeces but this will likely be a major cause of surface fouling (Radford et al., 2015).

The majority of reasons given by people in developing communities for upgrading their sanitation practices have nothing to do with the effect on their health or environment, which is what the SDG seek to improve. *Improved experience* and *social image* are key drivers that are often over-looked (Jenkins and Scott, 2007; Nawab et al., 2006). A review by Seymour & Hughes (2014) of user preferences and motivations in sanitation reported that prestige as a driver of adoption as being inconclusive indicated inconclusiveness regarding the significance of ‘prestige’ as a driver amongst both adopter and non-adopters of sanitation.

Rosenquist (2005) discusses the challenge of sustainable sanitation from the psychosocial point of view and identifies three key drivers that are also important to this paper.

- People tend to regard sanitation as an issue that is not of concern. Most people wish to avoid talking about the issue of excrement and the handling of it.
- There is a widespread lack of awareness about the quickly approaching sanitation crisis, and also of the benefits of using sustainable sanitation systems.
- So far, sustainable sanitation alternatives have had great trouble being adopted (Dellström Rosenquist, 2005).

Rosenquist states in her conclusion that new systems should appeal to people’s desires, but she also mentioned the importance of marketing to communicate benefits to the target market. This thesis will discuss what makes a toilet desirable in order to inform the design of future sustainable toilets, and hence improve their adoption. To do this, existing sanitation user interface technology will be reviewed – focusing on the user experience to identify key attributes and areas that require more research. Transferability of technology is of definite importance, as improved sustainable sanitation options are required for almost everyone in urban environments, regardless of wealth.

2.2 Reviewing current waterless and low-water toilets

A systematic approach to this literature review was taken (Denyer and Tranfield, 2009). The literature review was informed by the research objective: To review literature surrounding low-water sanitation options with a focus on the user experience. The first stage of this process was to search the database Scopus which includes access to the largest database of peer-reviewed literature. To answer this research objective the following search strings were used: (toilet OR sanitation) AND (technology) AND (user). This resulted in 242 articles which were reviewed for key words within the title and abstract to ensure relevance with the review objective. As the review objective focussed on technology and the user for sanitation, articles were removed if they focussed on excreta processing (*e.g.* bio-digesting technology) or handwashing related articles. This filtering and quality screening process resulted in 198 articles being discarded. Relevant references resulting from the resulting articles were also reviewed.

To give order to the review of different sanitation technologies (*e.g.* pit latrines, flushing toilets, container toilets), a monitoring tool was used as the starting point to discuss and compare the various technologies. The articles identified in the systematic review provided rich insight into current studies in this area, however additional sources were needed to ensure a thorough investigation of toilet technology. '*A collection of contemporary toilet designs'* by WEDC and EOOS (2014) and the online sanitation database on '*Engineering for Change'* were used to ensure a comprehensive selection of toilet technology was identified. Utilising peer reviewed literature as well as practical databases used by sanitation practitioners a comprehensive body of work from over 80 sources was produced.

The objective to review literature surrounding low-water sanitation options, with a focus on the user experience, was achieved by conducting a systematic review in conjunction with a state of the art review. The findings are discussed in the rest of this chapter.

2.2.1 Monitoring progress

Sanitation options in urban areas vary greatly depending on wealth, resource availability and space. To monitor the progress of Sustainable Development Goals, the World Health Organisation (WHO) developed the Sanitation Ladder[3]. The concept was updated in 2017 to include five levels as opposed to the initial four. 'Open defecation' is at the bottom rung, and at the top rung is 'improved facilities' which include: flushing/pour flush toilets, Ventilated Improved Pit latrines (VIP), composting toilets or pit latrines with slabs (WHO, 2017). It's worth noting however, that the flushing/pour flush contradicts one of the four Bellagio Principles that declared 'wastes are to be diluted as little as possible'. These principles were established specifically to address lack of sanitation in urban environments (Schertenleib et al., 2003). The Sanitation Ladder has also been criticised for classifying people as simply either having improved sanitation or not having it at all (Kennedy-Walker et al., 2014).

[3] The sanitation ladder is a monitoring tool to enable benchmarking and comparison of progress across countries at different stages of development (WHO, 2017).

Table 2 – The sanitation ladder (WHO, 2017)

Level	Description of what counts towards achievement of rung
Safely managed	Use of improved facilities that are not shared with other households, and where excreta are safely disposed of *in situ* or transported and treated offsite.
Basic	Use of improved facilities that are not shared with other households.
Limited	Use of improved facilities shared between two or more households.
Unimproved	Use of pit latrines without a slab or platform, hanging latrines or bucket latrines.
Open defecation	Disposal of human faeces in fields, forests, bushes, open bodies of water, beaches or other open spaces, or with solid waste.

A form of sanitation ladder presented in the UN Human Development Report (2006) presents seven different methods/technologies arranged in levels by cost per household. There is also a comment for each level, so at the bottom is 'open defecation' that costs nothing but is noted as causing "obvious problems for those who defecate and others". Kvarnström *et al*. (2011) suggested that the method for monitoring progress should focus less on the individual technologies available but instead the function they provide. This method allows for new technologies to be measured and compared more accurately, focusing on functional outcomes and the effect on the environment in particular (Gunawardana and Galagedara, 2013). Each rung on the ladder has a number starting with one at the bottom for most basic climbing to seven for the function new sanitation technology should be providing. The first four functions are health related and the top three are environmental functions. Although Kvarnström's model is comparing the total system, including processing, and this paper is focusing on the user interface, many important factors for the future of sustainable toilet technology are raised. The processing method will likely be the determining factor in users upgrading their sanitation considering cost and availability, but the user interface has to be designed to meet these requirements. The author states that it could be possible to use the ladder to identify and target 'selling points' for creating demand to move upwards on the ladder (Kvarnström *et al*., 2011).

Table 3 - Kvarnström's suggestion for an improved sanitation ladder (2011).

	Function provided	**Indicators**
Environ mental factors	7. Integrated resource management	Indicators will differ and depend on flow streams from the full environmental sanitation system (urine, faeces, greywater, faecal sludge, wastewater management and solid waste management) and context.
	6. Eutrophication risk reduction	Indicators will differ and depend on the flow stream from the sanitation system (urine, faeces, greywater, faecal sludge, and wastewater).
	5. Nutrient reuse	(i) X% of N, P, K excreted is recycled for crop production, (ii) Y% of used water is recycled for productive use.
Health factors	4. Pathogen reduction in treatment	Indicators will differ and depend on flow system (urine, faeces, greywater faecal sludge waste water) and also whether the flow stream will be used productively afterwards or not.
	3. Greywater management	(i) no stagnant water in the compound, (ii) no stagnant water in the street, (iii) no mosquitoes or other vectors
	2. Safe access and availability	(i) 24-hr access to facility year-round, facility offering privacy, personal safety and shelter, (iii) facility is adapted to needs of the users of the facility.
	1. Excreta containment	(i) Clean facility in obvious use, (ii) no flies or other vectors, (iii) no faecal matter lingering in or around latrine, (iv) hand-washing facility in obvious use with soap, (v) lid (odour-free facility)

The flushing toilet has changed little in the past two centuries and is yet is still the interface most commonly associated with the top of the UN sanitation ladder (Elledge and Mcclatchey, 2013). New user interface technology should be designed to be compatible or complementary with the upper stages of Kvarnstrom’s ladder, as this is will ensure sanitation closer to the needs of future urban populations.

> *“while the average American changes his automobile every two and a half years, gets a new suit about every nine months, buys a refrigerator every ten years, and even changes his residence about every five years, he never buys a new toilet bowl. If one could design the sort of bowl that would make people want to 'trade in' their old one, this industry would benefit greatly”.* (Papanek and Fuller, 1982)

The quote above from Victor Pananek’s seminal book *Design for the Real World* (1983) identified toilets as being a stagnant product with little improvement or variation. Arguably, this is still the case today. Even further back, in 1965, an ‘improved toilet’ was designed by Alexander Kira (Figure 10) to meet the real needs of users that – even by today’s western standards – could still be seen as revolutionary. He criticized the sitting position for defecation that has been widely acknowledged in literature as sub-optimal and argued that squatting is the more natural and healthier position (Mugure and Mutua, 2009; Sikirov, 2003). Few toilets in the western world today reflect Kira’s work, and the sitting toilet remains the norm. Cultural factors may play a role in this – the elderly or less able, for example, might find it difficult to use a toilet so low to the floor. The incorporation of a fold-out domestic urinal makes ecological sense but could face opposition because of association with public toilets and hygiene concerns.

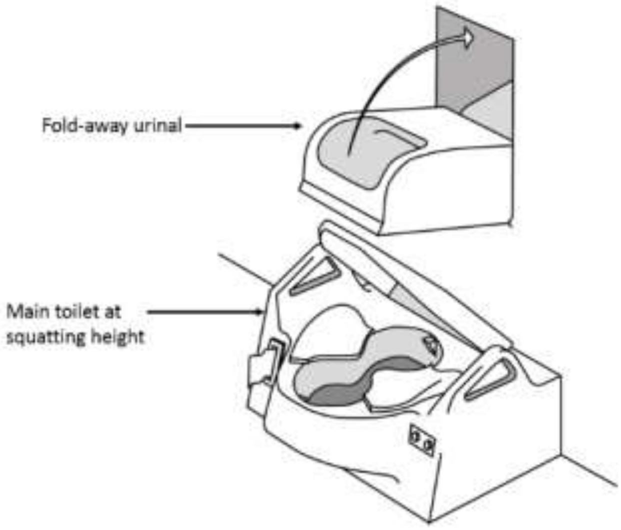


Figure 10 – 'Improved toilet' by Kira (1965)

It will be very difficult to make a waterless toilet to fit all scenarios, considering the variations between cultures, wealth, environment, aspiration and dwellings that exist across the huge number of people without sanitation (Nagy and Zseni, 2016; Swann et al., 2007). Seymour and Hughes (2014) found that users of improved sanitation facilities had greater levels of satisfaction with systems that use water e.g. western flush and ablution blocks. Given the ubiquitous use of water in sanitation, a water-free toilet may pose a challenge in the form of user resistance. It is likely that a range of technological innovations will be required to counteract such resistance, perhaps using different configurations in different localities, depending upon local cultural practices and expectations.

2.3 User interface options

Sanitation options for urban environments have been researched in the past (Chatterton, 2014; Katukiza et al., 2012; Langergraber and Muellegger, 2005; Otterpohl, Braun and Oldenburg, 2003; Paterson, Mara and Curtis, 2007) but with little discussion of the user experience. This thesis will focus on the user interface and user experience of toilets in urban environments and where performance can be improved and water saved. The water in a flushing toilet serves multiple functions relating to the user's experience (*e.g.* cleaning, odour prevention and transport) and to increase the likelihood of adoption of new low-water toilet technology, this high user experience should still be provided. How the excreta is processed will undoubtedly play a major role in user interface options: for example, flushing toilets should not be used if the excreta is intended to be composted. Likewise, without sufficient water the performance of a sewer system can become compromised (Littlewood, Memon and Butler, 2007). Ideally, toilet user interfaces should be pleasant to use, and be compatible with local processing methods without using excessive amounts of water.

To give structured progression to the series of toilet technologies reviewed, each level of Kvarnström's (2011) function-based sanitation ladder will be used as a base. This approach will be used to present compatible examples of user interface technology and to discuss the associated user experience. Using the UN's five-rung ladder would downplay the need for more innovation in this area, and constrain discussion of new alternatives to the flushing toilet. Kvarnström's ladder is divided, with the bottom half covering the importance of containing excreta. The higher tiers of the ladder are eutrophication risk reduction and resource management, so these will be covered by a large section on how to reduce water use in urban environments that are already connected to sewers and currently using large amounts of water per use. Although this ladder does not include open defecation, it is important to consider how to discourage this practice and instead promote the benefits of even the most basic of toilets.

2.3.1 Open defecation

Early man in hunter-gatherer societies could maraud the land and defecate with very little care, as excreta would simply degrade and have little negative impact (Niwagaba, 2007). As society moved from nomadic cultures to concentrated cities, human waste management became more of an issue and one that could not be ignored. 82% of the one billion people who practice open defecation live in just 10 countries, with India alone responsible for 597 million of those people (JMP, 2014). In rural India, a recent study found a surprisingly high number of people who didn't mind defecating outside, with 47% of respondents referring to it as pleasurable, comfortable and convenient and 12% referring to it as a habit or tradition. The report explains that many people believe latrines to be prohibitively expensive, and demand for latrines needs to be increased (Coffey et al., 2014). However, there are a number of negative aspects of defecating in the open such as attack by strangers or wildlife such as snakes (Mara et al., 2010b). Sustainable Development Goals 6.2 is to end open defecation by 2030 (WHO, 2017). Installing a household toilet for the first time can be a big decision that will likely involve the changing of household infrastructure as well as defection and faeces handling practices (Jenkins and Sugden, 2006). Community-Led Total Sanitation (CLTS) is a very effective and widely used approach to change attitudes and behaviours toward open defecation in developing rural communities. By demonstrating the negative aspects of open defecation the community discusses the implications, and themselves call for joint action. Communities take pride in declaring themselves open defecation free (Myers, Cavill and Pasteur, 2016; Sah and Negussie, 2009). Myers has discussed applying CLTS in urban environments, and provided a number of considerations – such as each case being context dependent, advocacy being needed from national, regional and international levels and improved co-production (Myers, Cavill and Pasteur, 2016).

2.3.2 Excreta containment

When the journey to a public toilet is not safe, especially for females or children, using a chamber pot or bucket to be disposed of later is an undignified but common practice in slums. Another notorious method is defecating in a plastic bag and throwing it away from the house – commonly referred to as a flying toilet (Anon, 2009). To improve this practice the Peepoo bag was developed by a Swedish organisation: its aim was to prevent the spread of disease in slum environments and refugee camps. The single-use biodegradable bag has an inner and outer layer to reduce the risk of faeces getting on the user's hands, and is filled with urea ($CO(NH_2)_2$) that reacts with the excreta to deactivate disease-producing organisms. In the most extreme situations, be it absolute poverty in slum conditions or emergency disaster relief, this is an effective way of preventing open defecation, and hence reducing the spread of disease at very low cost (Patel, Brooks and Bastable, 2011; Vinnerås et al., 2009). This should be the most basic option available to everyone in such scenarios; but, due to the lack of dignity and difficulty in use encountered by some, ideally it should only be considered a temporary option. During a trial period in Africa's largest slum, Kibera, on the outskirts of Nairobi Kenya, 90% of users strongly recommended its use. However, 60% of users voiced concern that the bag wasn't big enough (Anon, 2009).

2.3.3 Safe access and availability

In urban slums in the developing world, pit latrines are by far the most commonly used sanitation setup, with approximately 1.77 billion users (Katukiza et al., 2010b). The simple construction, zero water usage and low cost ensure the widespread usage across Africa, Latin America and Caribbean. Sugden (2014) declares that, when a family decide to invest in a latrine, it will have a number of common features whether they are in the Himalayas or in East Africa. What makes a latrine desirable is the same across the world, but improvements to these types of toilets have been slow over the years. Most latrines are notorious for bad odour,the appearance of cleanliness is key. (Grimason, 2000). Poorly built pit latrines can also pollute surrounding groundwater by contaminants leaching from the pit if the lining of the pit is insufficient or is compromised (Dzwairo et al., 2006).

Using a private latrine is better for the health of a family than using a shared public latrine, and facilitating the upgrade has to be a health care priority (Heijnen et al., 2014). Organisations are looking to drivers for adoption to work towards a demand-led approach, as opposed to centrally planned provision of infrastructure (Mara et al., 2010a). If demand for new technology is low then it's unlikely that the intended social benefit will be realised even if the product is provided (Ramani, SadreGhazi and Gupta, 2016). Most new household sanitation throughout the developing world is privately acquired, and without subsidy, which illustrates that this is a demand-led matter. 50% of the 2.95 million subsidized toilets in the rural region of Andhra Pradesh, India, were found to be unused or were being used for purposes other than sanitation (WSUP, 2007). Public-sponsored construction represents a very small fraction of the costs of household toilets implementation and improvement. Rosenquist (2005) raises the valuable point that policy-makers and politicians can harbour the same repulsive reactions to the topic of sanitation as everyone else.

The American Standard SaTo toilet pan shown in Figure 11, is an example of a micro-flush interface for pit latrines to improve user experience cheaply. It comprises a basic odour barrier that will only open when the user pours 0.15 litres of water into the pan after use. The two-part construction is simple, low cost and reliable method of preventing a continuous odour escaping into the toilet room. Local manufacture and an open-source design are a major benefit to this system, allowing for easy building and modification by tradesmen using available materials such as pipes and flat plastic. The odour from the pit below cannot pass into the toilet space. Further, insects cannot enter the pit, thus reducing the risk of disease transfer (Mecca, Davis and Davis, 2013a). Basic technology such as the SaTo pan is a simple and extremely low cost way both to improve user experience and to reduce disease transfer via insect vectors.

'*A collection of contemporary toilet designs'* by WEDC and EOOS (2014) and the online sanitation database on '*Engineering for Change'* were used as a starting point for this research.

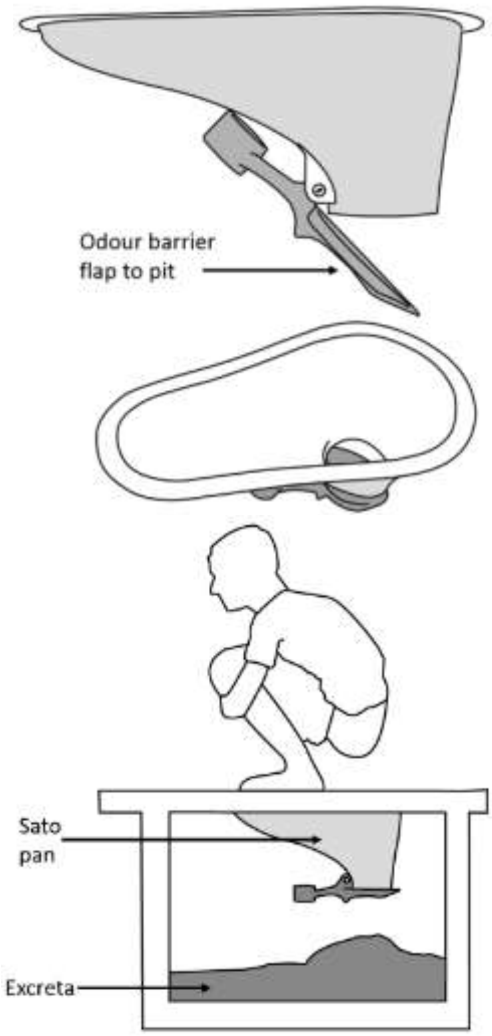


Figure 11 - The SaTo toilet pan by American Standard and a simplified drawing of it in use. (Tierney, R. 2017)

In Kumasi Ghana, a project called Clean Team backed by Unilever and WSUP provides a faeces collection service using a simple toilet (Figure 12) with a bucket filled with antibacterial chemical. The source-separating interface directs urine either to a container or directly into the gutter outside of the home – thus limiting the volume of waste going into the bucket and reducing demand on the collection service, which takes place two, three or four times per week. The service person removes the full bucket to take to a centralised processing plant and replaces it with a clean bucket with new chemical inside (Callow, 2012). The reasons given for users upgrading their sanitation practice from public toilets or open defecation to a Clean Team toilet fall within the reasons identified by Jenkins & Sugden 2006: lack of cleanliness, smell, convenience; improved ease of use for elderly users and those with young children, and improved safety, especially at night (Greenland et al., 2016). However, the same study also reports that some users commented that the current design is not suitable for small children, and modification to the design could be made.

Figure 12 - Urine-diverting Clean Team toilet. (Tierney, R. 2017)

2.3.4 Greywater management

Domestic water use in industrialized countries is approximately 100-150 l/c/d (litre/capita/day), of which 60 – 70% is transformed into greywater. The rest is used in toilet flushing and turned to blackwater. Reusing greywater to flush a toilet can reduce domestic water by 40 – 60l/c/d leading to a 10 – 20 % reduction

(Friedler, 2004). Toilets combining a hand basin on top of the toilet cistern (Figure 13), thereby allowing the greywater to refill the flush water are not only desirable for water-saving but also for space-saving too. These have started to become popular in small urban apartments and they are also being made by some of the most widely known toilet brands, such as Roca, a positive indication that water saving can be desirable (Fane and Schlunke, 2008). Although it's good to show an instant reuse of water, handwashing consumes a small amount of water compared with what's used during bathing and clothes washing – but it's a lot harder to direct water from these sources to a toilet.

Figure 13 - Example of hand washing reusing sink to reduce grey-water (Tierney, R. 2017)

Kvarnström states that that "to fulfill greywater management no stagnant liquid can be left in the compound or street to reduce the risk of mosquitos breeding". Although some Clean Team users divert urine into a container at the back of the toilet, many have a hose running outside of the property expelling the water into the street, which can create pools of liquid that provide breeding habitats for mosquitos. A London based organisation called Loowatt have developed a simple and effective method of removing excreta from the user to be safely stored in the unit. No open pools of liquid can be produced because of the sealing process of the interface. Each time a user defecates into the toilet a simple rotating, crimping mechanism packages the urine and faeces in a biodegradable film (Siegel, 2015). The excreta is collected regularly and used to produce biogas, killing pathogens whilst producing power. The system is odourless as the excreta is sealed, and there is no surface fouling because a new piece of film is used each time. Successfully piloting the system in Madagascar, and recently moving into servicing UK festivals, show the simple toilet service is viable for both ends of the economic pyramid (Loowatt, 2017a). The biodegradable film is the only consumable – and no water or power is required to use the toilet, which makes it a very promising off-grid option. The system requires no change to user behaviour: the excreta enters as a mixed stream and is contained together until collection for processing.

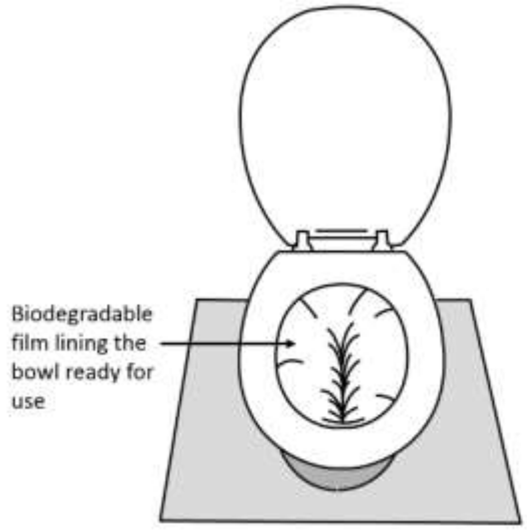


Figure 14 - Loowatt toilet with internal liner ready for use (Tierney, R. 2017)

2.3.5 Pathogen reduction in treatment

Incinerating toilets are self-contained systems that burn the excreta and paper inside the unit using electricity. They were first introduced by Sun Mar in 1966 for rural cottages Sweden (Sun Mar, 2017). The systems are expensive and energy intensive but have found a niche in cold climates unsuitable for normal composting (Anand and Apul, 2014). All bacteria is destroyed by the heat meaning only a safe ash remains. One example is the Cinderella toilet, where the user places a special paper layer down to catch all the excreta before it's dropped into the burning chamber. This means no faecal remnants remain on the toilet bowl as it's a new surface every time.

2.3.6 Nutrient reuse

Dry sanitation is primarily used in rural settings, and there are two main technical approaches if reuse is intended: decomposition (composting) or dehydrating. Dehydration processes the urine and faeces separately and often has additional absorbents (such as sawdust or ash) added to the faeces by the user after each use. Provided they are used correctly, reduced or absent odours associated with dehydrating toilets make them acceptable as a sanitation option (Moe and Rheingans, 2006). Odour has been noted as a user frustration in some cases however (Roma et al., 2013). Scandinavian countries are noted as being traditional industrialized countries that have adopted dry toilets in large numbers. The main driver for such adoption is usually their off-grid locations, low temperatures causing water to freeze, and their reduced environmental impact. Collection services of excreta for compost have been implemented in urban settings such as X-runner in Lima, Peru, and in Haiti by a group called Sustainable Organic Integrated Livelihoods (SOIL). The excreta is collected regularly and transported to a centralized site for composting and crop growth (Rao et al., 2016).

The Otji toilet is a urine-separating toilet pan that uses a novel internal shape to divert the urine whilst having faeces drop into a container below. A small trough that runs around the inside of the toilet collects any urine that hits the wall above the trough. It looks similar to a regular toilet so is less likely to cause confusion or generate a negative reaction from the user. Tests show that 80% of urine is separated at source with little contamination. The design is becoming popular in Namibia, but also in Latin America, with their self-build kits easing accessibility and ease of manufacture. Research into the adoption of the Otji design found that most users in Namibia were especially happy with the system as they would not have to pay for flush water – but authorities were still in favour of installing the flush toilet because it is perceived to be a high-class, modern solution (Ingle et al., 2012).

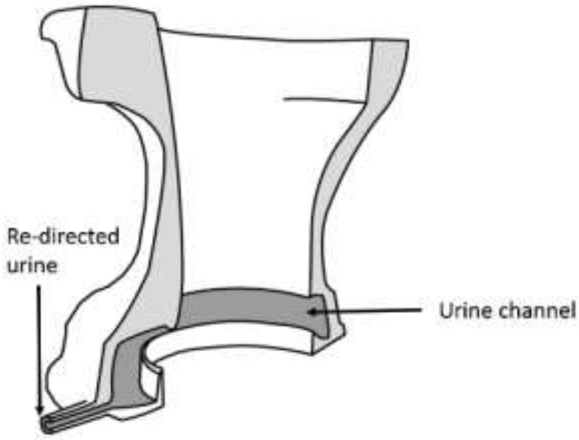


Figure 15 - Cross-section of the Otji toilet that separates the urine by directing it into the channel once it has hit the wall of the toilet (Tierney, R. 2017)

2.3.7 Water saving

Flushing toilets that give the option of a full flush for defecating and a reduced flush for just urination can decrease the amount of water used by 50-70% without affecting infrastructure, but they do present the user with a new behavioural choice. Although other low water toilets exist, it's only dual flush that requires the user to make a choice before they flush. (Arocha and McCann, 2013; Proença et al., 2011). American flushing toilets used to use 13 litres of water per flush, and some used up to 18 litres per flush; but after the Water Conservation act of 1992 was signed, toilets using over six litres were prohibited. This led to people importing toilets from Canada to ensure their toilets flushed with enough power. European toilets had been flushing with six litres for years and worked fine – the problem for American toilets using six litres comes from the nature of the siphonic flushing that they employ (George, 2008). A patented toilet design not yet in production intends to reduce this water usage by utilizing the weight of the flushed water to move a flexible section of pipe at the back of the toilet. This action will maintain the function of the water to clean and empty the bowl, ensuring good user experience, but with a 75% reduction of water used (Lee and Lee, 2003).

Ultra-low flush, otherwise known as air-assisted toilets, are toilets that use less than 2 litres per flush, and are ideal for scenarios where water is scarce but additional power is available. Airplanes use a vacuum to transport the excreta to holding tanks but require considerable power to do so. The user experience of vacuum toilets is positive. (Jenssen et al., 2003). Propelair is a UK based company that has recently began installing air-assisted flushing toilets into commercial properties in London and Swindon. The user closes the transparent lid of the toilet after use and presses a handle as normal: 1.5l of water is used, supplemented by high volume, low pressure air to clear excreta from the bowl. As the system does not work with a vacuum, the system is connected to the normal drain system (Fane and Schlunke, 2008). There is concern that low volume flushes will lead to blockages due to insufficient water, and – to mitigate this risk – consideration has to be given to the drainage system these toilets will be used in conjunction with (Littlewood, Memon and Butler, 2007). Vacuum assisted systems have great potential for the future of urban development. Providing an acceptable user experience and reducing water usage by 84% is certainly a positive step forward that all new developments should be seriously considering. The long-term money saving benefits of these systems would also be highly desirable to people even if they are not environmentally conscious (Littlewood, Memon and Butler, 2007).

A urine-diverting toilet system has been combined with a vacuum flush by Singapore University to reduce dilution of faeces and direct the excreta to a bioreactor for biogas production (Rajagopal et al., 2013). The urine-diverting dry (UDD) toilets, also known as no-mix toilets, have a physical barrier within the toilet pan that is anthropometrically positioned to allow faeces to drop straight below the urine, which comes out of the body at more of an angle, to be separated. UDD toilet system is a urine-diverting toilet system that uses water to flush faeces to the normal sewer but allows for safe urine capture. They generally require more attention than pit-latrines but warrant it by the lower environmental pollution and improved user experience through reduced odour (Rieck, Von Munch and Hoffman, 2012). A review on acceptance was overall positive about the systems, with 80% of 2700 respondents from seven European countries regarding UDD toilets as a good idea. This is encouraging, considering that 60% of users encountered problems. Design improvements are recommended to address the following issues: faeces and urine going into the wrong compartment, causing more cleaning and loss of nutrients; the necessity to sit to urinate; and difficulties children have with use. Referencing Everett M. Rogers, the author also states that, given the drawbacks of currently available no-mix toilets, it is difficult to imagine a take-off of this innovation (Larsen, T. A., Udert, K. M., & Lienert, 2013; Lienert and Larsen, 2010).

Foam-flush toilets use a biodegradable soap that foams around the rim and covers the bowl after each use instead of using water. A small fan in a detergent produces the bubbles that provide comfort, cleaning and excreta conveyance commonly into a household composting unit (Anand and Apul, 2014).

Domestic urinals are practically unheard of in western society but could have massive water saving potential once user perception barriers are addressed. There is very little mentioned in literature on the subject, but an online article by the British newspaper *The Guardian* posed this question to readers. There was wide acknowledgment that the water wasted was excessive, but there was also a rather strong objection to the idea of domestic urinals being the best solution to this. The majority of comments consisted of repulsion and concerns around cleaning, but the fact that it is a ‘male only’ object also was a major factor (Hickman, 2010). The ‘improved toilet’ by Kira (1965) included a fold out urinal that would alleviate some of the issues of space and cleanliness, but could also reduce the shock factor of a domestic urinal.

Waterless urinals are becoming relatively common in new-build commercial properties and when updating existing systems. Odour is prevented using a floating oil trap or with a physical barrier such as a very thin self-closing plastic tube that allows liquid to pass through via gravity and then recloses to prevent odour moving in the other direction. Sports stadia offer an opportunity for large quantities of undiluted urine to be captured and the nutrients recovered, instead of being channeled into the sewer as is normally the case (Bristow et al., 2004).

2.4 Common frustrations declared by users of low-water toilets

Rosenquist (2005) stated "the human experience plays a major role in the future of each sanitation project", so now the root cause of user frustration, and the response that is evoked, will be presented to give a clearer definition of the problem to be addressed.

User Issues	Cause of issue	Response from user	How water addresses the frustration
Faecal fouling visible on toilet	Faeces of previous user sticking to visible surface.[1]	Visual disgust and perception of uncleanliness[2]	Flushed water washes pan but is not entirely effective. Well-maintained toilets also have a toilet brush for additional cleaning by the user.
Visible faeces being stored (*e.g.* inside pit latrine)	The average adult produces 128g of faeces per day, consisting of approximately 75% water, with a frequency of between 0.21 and 2.54 per day[3]. Method of storage, volume and frequency of processing will determine user experience.	Belief that presence alone can cause illnesses such as: Constipation Stomach ache Cholera [4]	Approximately nine litres of water are used to carry excreta away after each use, over the U-Bend and into the sewer pipes.
Odour	Toilet malodour consists of a complex mixture of Volatile Organic Compounds	The smell of faeces is consistently rated as the most intense,	Once faeces falls below the water line,

	(VOCs) produced by faeces, but the main odour of faeces is generally attributed to: fatty acids, Sulphur-containing, compounds, Indole, Skatole , Ammonia [8]	unpleasant and most dangerous smell, and is described as: Foul, Striking, Putrefaction [8,9]	the amount of odour given off is reduced.
“Heat” (Noted in some developing countries as the miasma from other people’s faeces transferring disease7).	Exothermic metabolic activity takes place in pit latrines, and the common perception is that warm air rising from other people’s faeces carries disease [5,6]	Fear of contraction of disease, in particular Candidiasis, often referred to as “white”.[7]	Disposing of faeces with water gives the user the desirable ‘flush and forget’ experience, and prevents users from coming in contact with previous users’ excreta .

Table 4 shows the four main frustrations that cause visceral disgust when using a toilet. In each case, the role that water can or does play in mitigating such frustrations will be identified.

The toilet is a typical source of offensive odours in everyday life (Sato et al., 2002). Faeces are considered the most unpleasant of odours to humans and a prominent stimulus for disgust and repulsion (Afful, Oduro-Kwarteng and Awuah, 2015). The belief of faecal odour causing contamination of the air and disease has existed since ancient times and is a reason some people still prefer to openly defecate rather than use a latrine (Rheinlander et al., 2013).

Table 4 - User interface frustrations and causes, with possible design opportunities to address (references below[4])

User Issues	Cause of issue	Response from user	How water addresses the frustration
Faecal fouling visible on toilet	Faeces of previous user sticking to visible surface.[1]	Visual disgust and perception of uncleanliness[2]	Flushed water washes pan but is not entirely effective. Well-maintained toilets also have a toilet brush for additional cleaning by the user.
Visible faeces being stored (*e.g.* inside pit latrine)	The average adult produces 128g of faeces per day, consisting of approximately 75% water, with a frequency of between 0.21 and 2.54 per day[3]. Method of storage, volume and frequency of processing will determine user experience.	Belief that presence alone can cause illnesses such as: Constipation Stomach ache Cholera [4]	Approximately nine litres of water are used to carry excreta away after each use, over the U-Bend and into the sewer pipes.
Odour	Toilet malodour consists of a complex mixture of Volatile Organic Compounds (VOCs) produced by faeces, but the main odour of faeces is generally attributed to: fatty acids, Sulphur-containing, compounds, Indole, Skatole , Ammonia [8]	The smell of faeces is consistently rated as the most intense, unpleasant and most dangerous smell, and is described as: Foul, Striking, Putrefaction [8,9]	Once faeces falls below the water line, the amount of odour given off is reduced.
"Heat" (Noted in some developing countries as the miasma from other people's faeces transferring disease7).	Exothermic metabolic activity takes place in pit latrines, and the common perception is that warm air rising from other people's faeces carries disease [5,6]	Fear of contraction of disease, in particular Candidiasis, often referred to as "white".[7]	Disposing of faeces with water gives the user the desirable 'flush and forget' experience, and prevents users from coming in contact with previous users' excreta .

[4] References: [1](Ward, J. 1976) [2] (Sugden, S. 2013) [3](Rose. C, 2015) [4](Obika, A. 2002) [5, 6] (Kimuli, D. 2016) (Obika, A. 2002) [7](Jenkins, M. W. & Scott, B. 2007) [8](Chappuis, C, 2015) [8, 9] (Tuhkanen, T. 2012) (Afful, K. 2015) [10, 11](Sato, H. 2003) (Seo, Y. 2013)

2.5 Assessing design opportunities

Four examples of technological features to address these major frustrations are now presented. These each have the potential to improve the user experience with several of the toilets profiled in the earlier section.

Extraction fans: By withdrawing the odour at the source, a significant amount of cause for negative user experience will be eliminated, rather than relying solely on a bathroom extraction fan. This is very important as faeces are normally submerged in flushing toilets, limiting the amount of VOCs that can reach the user – which does not happen with dry toilets. Additionally, fears around ‘heat’ and disease transfer can also be eased. Seo & Park (2013) modelled the effectiveness of such an extraction system. Its implementation could be a simple and effective method of removing odour, and also of alleviating concerns of disease transfer. This might be achieved by using one suction point and a perforated tube following the underside of the bowl. Solar-powered pit latrine versions could be used to improve the extraction of VIP pit latrines equipped with the Sato flapper pan. Odour can transfer from the pit to the user when opened so, if a small fan can be triggered by the act of opening, then smell can be removed. Consideration has to be given to ventilation so that it works effectively – and also to ensure that odour isn’t inadvertently encountered by others: for example, by walking past the outhouse into the path of extracted air. Odour sequestering technology, such as the SOG kits used on mobile homes, use carbon filters to limit unpleasantness for people nearby.

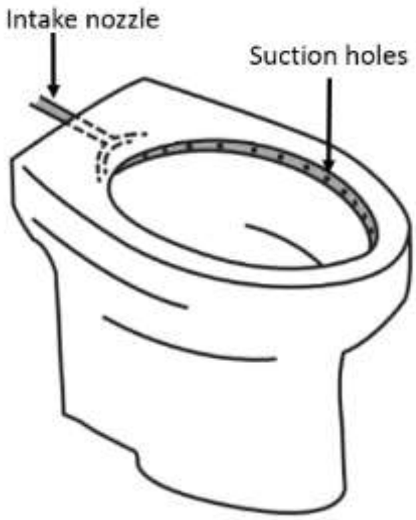


Figure 16 - Odour extraction testing (Seo & Park, 2013) (Tierney, R. 2017)

Physical barrier: Similar to the extraction fan, this would combat two major frustrations: fear of ‘heat’, and the sight of others’ faeces. Portable toilets have primitive physical barriers whereby the user cannot directly see into the holding tank below because of the angle of the opening. Faecal fouling is likely with a physical barrier, or any surface that faeces comes in contact with, unless a non-stick or sacrificial surface is used.

Non-stick surfaces: It’s common for domestic flushing toilets to have a toilet brush to clean any faecal fouling after use, but preventing this fouling occurrence in the first place – with surfaces that repel faeces – would greatly improve user experience. Faecal fouling on the surface of waterless toilets will be more likely than in a flushing toilet – and an ongoing source of user frustration. The Cinderella incinerating toilet evades this problem by having a paper lining inserted by the user before each use. This is not only an extra consumable required by the toilet, but will also be an inconvenience for the user.

Odour neutralizing: Commercial products exist that neutralize odour using ozone decomposition and ultraviolet light in various configurations. There are domestic varieties that can be attached to the underside of any toilet lid to clean inside the toilet once the lid is closed after use, thus providing a potentially smart way to improve user experience. There is, however, little in literature that empirically tests the effectiveness of these products. Dark surfaces may prevent the user from being able to easily notice faecal fouling, but any surface fouling will increase malodour, which is not ideal. Killing the odour inside pit latrines may reduce attraction to insects and limit disease transfer through that route.

2.6 Identifying design innovations across the sanitation ladder

The goal of Sustainable Development Goal Six is for everyone around the world to have sustainable management of water and sanitation. For this to happen innovation is needed across the whole sanitation ladder. Table 4 shows the updated sanitation ladder proposed by Kvarnström (2011) with additional columns after the vertical line showing opportunities to improve the user experience at each stage. After the vertical line, an example of a sanitation system that meets the required function is given, followed by an example of an associated frustration and, finally, an opportunity for a new design to address this.

Table 5 - Identification of frustrations associated with technologies on the sanitation ladder, and opportunities to address them to encourage adoption of new technology and progression up the improved sanitation ladder by Kvarnström (2011)

	Function provided	Example of system	Frustration/ problem encountered by user	Opportunity for improvements to user interface
Environmental factors	7. Integrated resource management	Foam flush	Skepticism of performance	Changing perception that flush is best
	6.Eutrophication risk reduction	Ultra-low water flush	Skepticism at performance	Large toilet manufacturers making desirable ultra-low flush toilets using under 1.5 litres
	5.Nutrient reuse	Dry sanitation	Visible faeces	UDDT Otji bowl Improved urine-diverting toilets Physical block between user and excreta
Health factors	4.Pathogen reduction in treatment	Incinerator	Complexity Ventilation	Self-loading paper insert
	3.Greywater management	Sealing toilet	Location availability Odour during use	Cost, ease of collection Odourneutralising
	2.Safe access and availability	Private pit latrine	Odour Cleanliness Size & location Cost	Passive ventilation Non-stick surfaces Extraction fan Compact self-contained variations
	1.Excreta containment	Peepoo bag	Comfort in use	Apparatus to hold peepoo during use

2.6.1 Areas for further research

1. Low cost non-stick surfaces:

Faecal fouling was a major frustration noted for people at the bottom of the pyramid, but it is also a frustration for people at the top of the pyramid – as most western homes have a toilet brush to clean anything remaining on the pan. Improved non-stick surfaces would hugely reduce this. Omniphobic surfaces have not been used for sanitation purposes yet, but there is great potential for materials with their qualities able to repel substances with low surface tension.

2. Passive problem solving:

The clever shape of the Otji system alleviates the main barrier to UDD toilets without compromising function. Although the adoption of the Otji is not currently widespread, it has been shown to be well received on trials, giving users “the convenience of poo and forget” (Ingle et al., 2012). Adapting this design to incorporate a vacuum flush similar to the No-Mix design could be an interesting toilet. Using creativity to overcome a challenge and improve user experience in a passive manner should be the approach for tackling other challenges within new toilets.

3. Low cost/low power smell mitigation:

As odour is such a cause of negative associations with toilets, simple passive methods of extraction would greatly improve the user experience of many systems, especially for people who use shared facilities. The VIP latrine performs this task relatively effectively, provided all of the excreta is in the pit, rather than poorly aimed and hitting the side causing surface fouling.

4. Self-contained household toilets:

Compact, self-contained toilets are needed to give people in slums private sanitation options, especially for night use and for females. This will encourage the development of new slum housing to consider toilet space as a major issue in reducing reliance on public facilities. These will have to be pleasant to use but also discreet enough so that they are unnoticed when not in use.

5. Changing the 'the flush is best' perception:

An observation by the report into acceptance of the Otji toilet (Ingle *et al*., 2012) stated that the Otji is seen as an inferior product because it is compared to the flushing toilet. Similar statements surrounding the superiority of the flushing toilet have been noted in other literature (Antoniou et al., 2015; Sugden, 2014). Although it's important that product options improve, it's also important that attitudes towards flushing have to change in order for low water solutions to become a desirable option. Awareness is needed to show how wasteful flushing toilets are. The Relative Advantage described by Rodgers (2010) of new low-water solutions can be more easily shown if perception of the existing flush toilet becomes tarnished, as people accept it is an unsustainable technology. Similar techniques can be employed to help decision makers choose the more sustainable option. Having large toilet manufacturers make a real effort to reduce the water used by their toilets will also help.

In Japan, toilets are not hidden away as something to be embarrassed about (George, 2008). They have moved past their normal function to contain a range of features and novelties making them desired objects to be proud of. This is the shift in perception that will generate the greatest change moving forward throughout the rest of the world. Japan has led the high-tech toilet revolution in recent years. Sitting toilets with integrated bidet systems are present in 63% of homes in a country where squatting pit latrines were the norm sixty years ago. The toilets are gadget-laden and wasteful, but it's where toilet innovation is being celebrated. The high-tech toilets have largely been ignored by the rest of the world, but it is an interesting concept that – by shifting the perception of the toilet from a thing of convenience to something to be desired – the demand for technology has created a new market and new behaviours amongst users (Adhiutama et al., 2009; Tripsas, et al. 2009).

2.7 Chapter analysis

Toilets are vital to everyday life but remain a 'taboo' subject in many parts of the world. For progress to happen, it is important to acknowledge their value but also to recognize the aspects that need improving. New technology is needed to separate the user from the excreta in a sustainable way that is convenient and pleasurable to use, across the whole sanitation ladder. Availability and user experience are poor for people in developing countries, whilst the desirable flushing toilet is terrible from an ecological perspective. Removing frustrations associated with toilets will help increase the desirability of new technology, and ultimately increase the adoption of improved systems and progression up the sanitation ladder. The key frustrations are caused by the repulsion associated with faeces, especially from other people. Encountering the sight and smell of faeces leads to a belief that a toilet is unhygienic and will cause disease. Technological challenges and user experience will have to be considered together to address problems on an individual, contextualised basis, with common themes across the board – such as prevention of odour, perceived cleanliness, and no evidence of previous users. Physical barriers blocking users from stored faeces in pit latrines is an example of a simple method of improving user experience and preventing access to flies and insects that spread disease. Improving non-stick surfaces will be hugely beneficial for the future of low water toilets as they improve the user experience and help ease the movement of excreta through the system without water. As odour is such a major frustration, simple methods of mitigating smell such as integrated ventilation and extraction are needed. New sanitation options have to be demanded by the user rather than imposed by external sources, and good user experience makes such products more desirable. Innovation is desperately needed across the whole sanitation ladder whether it is to improve user experience, provide a self-contained toilet or reduce an unsustainable amount of water.

2.8 Chapter Two highlights

Objective Two commenced with investigating the current state of sanitation around the world identifying the need for better sanitation options for users in developing countries and a reduction of the amount of water used in by people in developed countries. The profiled technologies were structured using Kvarnströms sanitation ladder with a focus on user experience. The main frustrations of the technologies were identified and opportunities for new technology to reduce water whilst maintaining user experience. The following objective will look at people in the primary target market of Kumasi, Ghana to gain an understanding of the toilets they use and how lack of access to household sanitation affects daily life.

“She told her husband if he didn’t get her a toilet, she wanted a divorce!”

Ghanaian Respondent 06 (2015)

3 EXAMINING THE PRIMARY TARGET MARKET: KUMASI, GHANA

Objective Two: *To identify and analyse the frustrations and perceptions associated with using different toilets by residents in Kumasi, Ghana (the project's primary target market).*

Around the world, 2.1 billion people lack access to improved sanitation meaning a variety of alternate methods have to be used when needing to relieve oneself (WHO, 2017). This primary research sought to gain a deeper understanding of people who live in an area with poor sanitation coverage. The three key stages of the chapter are presented in Figure 17. These stages comprised of the objective background, the collection of data and the key findings and insights of the objective. A user persona for each technology will be presented to humanise the statistics that are often difficult to comprehend due to scale.

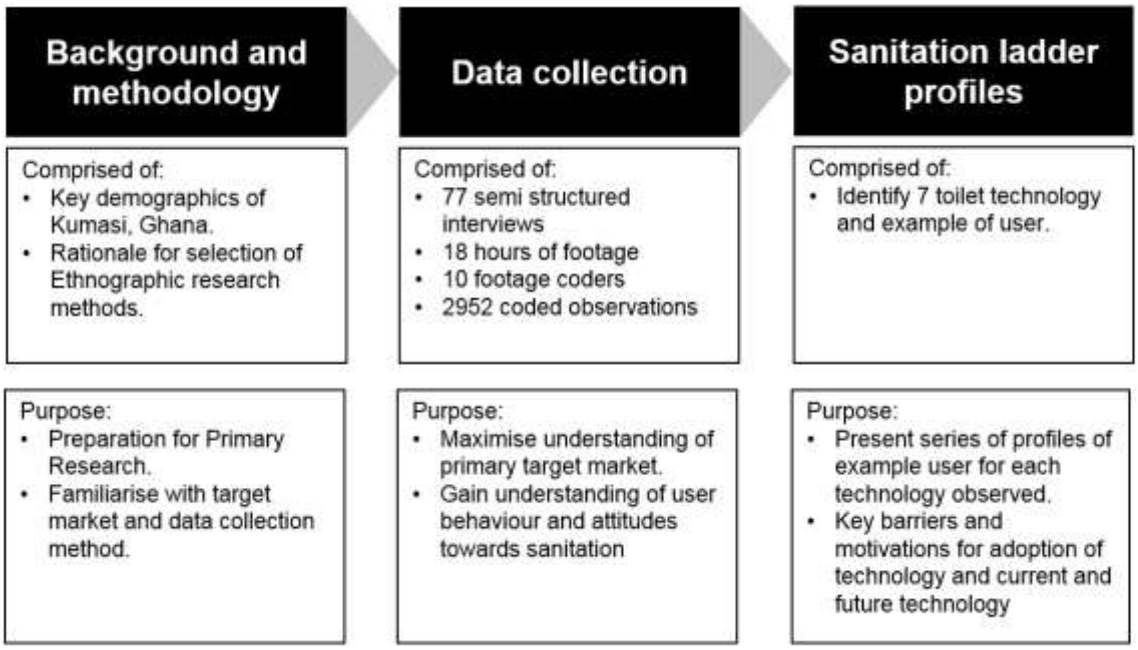


Figure 17 - Chapter structure and rationale of Objective Two

3.1 Background information on Kumasi, Ghana

This research is part of the Nano Membrane Toilet (NMT) project and Kumasi, Ghana is the primary target market for the toilet being developed. This was chosen due to an existing partnership with the organisation Clean Team, who are based in the town and were able to facilitate the research. Kumasi was also the location for the first research trip that took place in 2013 (Tierney, 2014). Ghana has made significant progress in recent decades in providing access to improved water supplies with 88% of the population having access to water. However, the country is still considerably behind on ensuring access to improved sanitation, with only 14% of the population using at least basic sanitation[5] (WHO, 2017). This means that most of the country either practices open defecation, uses unsafe toilets, or uses shared facilities. Kumasi is the second largest city of Ghana, and the capital of the Ashanti region located 250km North West of Accra, the national capital.

Half of Kumasi's two million population, live in high-density areas often with poor infrastructure. Only approximately 300 dwellings in a small area in the city centre are connected to the sewage network (Greenland et al., 2016). The city's sewerage infrastructure is outdated and unable to meet the demand of its inhabitants, as most of it was built in the 1970's when the city had a population one-third of what it is today (Keraita, Drechsel and Amoah, 2003). This leaves 43% of residents using toilets connected to septic tanks and 36% using fee-charging public toilets of varying quality and comfort (Greenland et al., 2016). In 2015 an investigation by the organisation World Sanitation for the Urban Poor (WSUP) (2016) into the quality of the city's public toilet facilities was conducted by rating them against nine criteria. These include cleanliness of the external surrounding toilet, functionality of containment structure, internal cleanliness of toilet, internal lighting and ventilation, availability of washing facilities, customer

[5] 14% country average for using basic sanitation, 9% in rural areas and 19% in urban areas (WHO, 2017).

responsiveness of management, appropriateness of fees, communication and signage, and safety, security and privacy. Out of the 419 public toilets assessed, only 14 received a satisfactory score underlining the need for vast improvements to the sanitation options in the area (WSUP, 2016). A bucket latrine system was common throughout Kumasi until being recently being outlawed and could either be kept in the house or in a separate outhouse, but most importantly the bucket had to be accessible from the street. This normally meant a small wooden door that allowed a collection person, who was often referred to as the 'night-soil collector', access to remove the excreta (Van Der Geest, 2002). The practice has been outlawed in recent years due to the night-soil collectors often disposing of the excreta improperly and dumping the human waste in the local environment.

To improve the sanitation situation of Kumasi and give more people the option of an in-home toilet, a service called Clean Team was funded by WSUP and designed by IDEO.org[6]. The project started in 2010 with IDEO using human centred design techniques such as 'shadowing' and 'inspiration cards' over the course of six weeks to build up a rich understanding of the target area, the current problem and the target market. After six weeks they were testing prototypes with the residents before developing the full service and running the first pilot project in 2012 (Callow, 2012). Whilst in Kumasi, the Clean Team service person explained the price of the service to the researchers before the interviewing began. The price the user pays for the service per month ranges from 25 Ghanaian cedis - 45 Ghanaian cedis (approximately $5.50 USD - $10 USD). This price depends on the amount of collections they require, for example if they want two, three or four collections per week, which would be determined by how much it is used. This is similar to the amount paid by Kumasi residents to use the public toilets.

[6] IDEO.org are a division of the renowned design firm IDEO who focus on humanitarian challenges based in San Francisco, USA.

3.2 Research rationale

The initial research trip to Kumasi, Ghana was conducted during the first phase of the Nano Membrane Toilet Project in March 2013. This was a sensitization trip to introduce the project. The purpose of the trip was to gain a basic understanding of sanitation in the area. The second research trip, which is the focus of this objective, took place in January 2015 and was more in-depth and rigorous. The research was facilitated by Clean Team who provided translation, navigation and access to Clean Team customers and non-customers. The non-Clean Team customers used a variety of other toilets which was another reason why Kumasi was a suitable location for the research to take place. The research approach was approved by Cranfield University's Science and Engineering Research Ethics Committee (SEREC) and consent forms were given to participants who took part in the research. This informed the participants that their data would not be used publically in any manner that could lead to their identification. Four researchers took part in the research trip to Ghana that lasted for two weeks. The team was divided into pairs with two separate approaches. The first pair of researchers were from the water science department that used a survey research method with the aim of obtaining core data such as house sizes, populations and acceptance of technology using a Likert scale. Their findings were presented in a conference paper (Cruddas, Parker and Gormley, 2015). The second pair of researchers were from the design department and used 'shadowing', 'contextual interviews' and 'systematic observations' which are examples of ethnographic research techniques. Ethnographic techniques have been adopted by a number of large companies such as Ford, Hewlett-Packard and Whirlpool, leading to a wide variety of successful innovative products (Goffin et al., 2012). This approach allows for deep consumer insights to be gathered on a sensitive subject. The ethnographic research methods were advised by Prof. Keith Goffin, professor of Innovation and New Product Development at Cranfield University School of Management and author of the book 'Identifying hidden needs: creating breakthrough products' (2010) that was used for planning this research.

3.2.1 Preparation for research trip

Preparation is crucial to maximise the findings whilst using ethnographic methods. As Fetterman writes in the book ‘Ethnography: step by step’ (2010) “The ethnographer enters the field with an open mind, not an empty head”. This means the researchers must be prepared with key areas of interest to raise with the respondent but open to their responses rather than dominating with preconceived notions. The basis for the semi-structured interviews taking place in Kumasi, Ghana were based on the Integrated Behaviour Model for Water, Sanitation and Hygiene (IBM-WASH) model shown in Table 6. This model was chosen because it is a synthesis of existing theoretical models, such as decision making and explanatory frameworks. The model was developed from a systematic review investigating factors that affect behaviour associated with water and sanitation (Dreibelbis et al., 2013). The model has been tested and refined in the field and has been used by other researchers investigating behaviour and technology in the WASH sector (Hulland et al., 2013).

Table 6 - IBM-WASH model (Dreibelbis et al., 2013)

Levels	Contextual factors	Psychosocial factors	Technology factors
Societal/ Structural	Policy and regulations, climate and geography	Leadership/advocacy, cultural identity	Manufacturing, financing and distribution of the product; current and past national policies and promotion of product.
Community	Access to markets, access to resources, built and physical environment	Shared values, collective efficacy, social integration, stigma	Location access, availability, individual vs collective ownership/access and maintenance of the product.
Interpersonal/ household	Roles and responsibilities, household structure, division of labour, available space	Injunctive norms, descriptive norms, aspirations, shame, nurture	Sharing of access to product, modelling/demonstration of use of product.
Individual	Wealth, age, education, gender, livelihoods/employment	Self-efficacy, knowledge, disgust, perceived threat	Perceived cost, value, convenience, and other strengths and weaknesses of the product.

Habitual	Favourable environment for habitat formation, opportunity for and barriers to repetition of behaviour	Existing water and sanitation habits, outcome expectations	Ease/effectiveness of routine use of product.

The IBM-WASH model has three dimensions (contextual factors, psychosocial factors, and technology factors) that operate on five levels (structural, community, interpersonal/household, individual and habitual) that intersect (Hulland et al., 2013). The model provided the key themes for the semi-structured questioning to take place in the home of the respondents. As shown in Table 7, the model was simplified to make it easier for the design team to reference it whilst undertaking the contextual interviews.

Table 7 - Simplified IBM-WASH model for design team use in Kumasi

	Contextual	Psychosocial	Technology
Structural	Geography	Identity	Finance, Manufacture & distribution
Community	Resources	Stigma	Availability & maintenance
Household	Responsibility	Descriptive norms & shame	Location & space
Individual	Wealth	Risk & disgust	Attitude
Habitual	Access	Outcome expectation	Ease of routine

To ensure the researchers were comfortable with the interviewing process and techniques, several practice interviews were conducted with Cranfield University researchers. These interviews involved the researchers answering questions about two different toilets with the interviews and demonstration recorded and assessed.

3.2.2 Contextual interviews and demonstrations

In total 52 Clean Team customers were interviewed and 26 non-Clean Team customers were interviewed using the IBM-WASH model as the basis for questions. Of the 78 interviewees, 53 were female and 25 were male. The interview would begin with simple questions such as ‘the number of inhabitants’ and ‘what type of toilet they used’, before asking questions based on the themes from the simplified IBM-WASH model. One researcher would ask the questions, the other would record the footage and ensure all themes were covered. In the book, ‘The art of Fieldwork’ (Wolcott, 2005), some fundamental qualities of good interviewing technique are outlined, such as the importance of being an ‘active listener’. This is a crucial part of the laddering technique whereby the interviewer picks up on important answers and asks the respondent to explain further to gain a deeper understanding of the responses by finding subconscious motives (Wolcott, 2005). Once the key themes had been covered and both researchers were satisfied with the responses, a demonstration of use was requested. A demonstration of cleaning was then given to see further user-product interaction. An aspect of interest during demonstrations was to distinguish if the responses were consistent with their answers from previous questions. For example, a user would say they cleaned the toilet every two days but during the cleaning demonstration they would not be able to find the cleaning equipment which would suggest they are exaggerating or not telling the truth.

3.2.3 Systematic observations of footage

An observation team was assembled on return from Ghana to review the footage. The team was comprised of eight innovation researchers, one Ghanaian translator and the two original researchers acting as facilitators for the process. The researchers were grouped into four trained teams to observe separate key topics[7]. The four topics were determined by the two primary researchers

[7] ‘Environmental surroundings’, ‘Reason for acquisition’, ‘Actions’ and ‘non-verbal communication’

discussing what would be valuable to inform future toilet technology to improve sanitation in the area. Each topic comprised of between five and nine observations for the teams to identify. For example the team responsible for spotting 'Use' would record an observation of 'misuse' if they saw a respondent incorrectly use a product and would then type a brief description of what they saw. There was 18 hours of footage that were analysed once a week, over a number of months.

Figure 18 - Systematic observation session with eight master's researchers and one Ghanaian national

The observations were recorded on a live spreadsheet noting what was observed, the time it took place and comments giving more detail on what was seen. At the end of each video a discussion took place about key points of the video to ensure an accurate recording of events agreed by the whole observation team.

Respondant	Time	Observed	Notes	Code	Date	Length	Male/Female	No in Household	No using Toilet	DMU
1	05:45	a	If she is pregnant, it would be more convenient to use the toilet	conven	07.01.15	08:37	f	4	4	mother
1	05:45	a	If she is pregnant, it would be more convenient to use the toilet	collective	07.01.15	08:37	f	4	4	mother
1	06:20	cult	Lots of husbands retain decision to purchase a toilet (therefore rare she making decision without husband to purchase toilet)	collective	07.01.15	08:37	f	4	4	mother
			He is priest - Can stay in his room for up to a month at a time therefore needs toilet in home. Needs to							

Figure 19 – Extract of the live document that was used in the systematic observation session showing raw data of which 1442 observations recorded.

3.3 Findings from systematic observations

The observations were compiled into lists and were discussed by the observation teams. Their task was to identify the overall patterns within the main observations and summarise into concise statements that gave a fair summation of the codes. These statements are explained in more detail below and in relation to the original topic that were used to divide the researchers into pairs for the observations. For example, in an interview when a mother expresses frustration at her child for misusing the toilet and making a mess with sawdust. The observation would be **Use**[8] with the codes; *Frustration*[9], *collective* and *cleaning*. In total, 36 different types of observation were recorded and 2952 codes were identified.

[8] Observations will be written in **bold**
[9] Associated codes will be written in *italic*

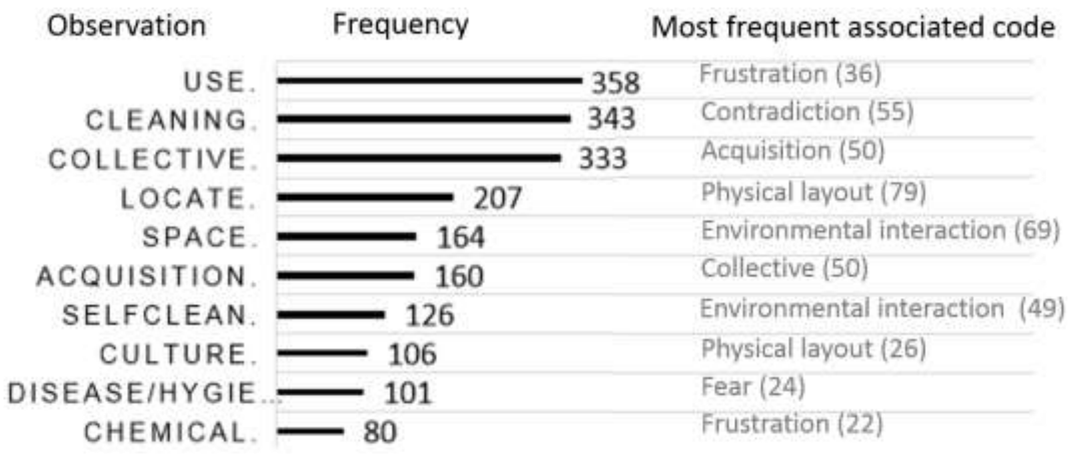


Figure 20 – The ten most frequent observations out of the 36 encountered throughout the footage. The observations recorded displayed alongside the most frequent code associated with each Observation and the number of instances for each.

3.3.1 Thick description for each topic

A thick description will now be presented for each of the systematic observation teams to summarise what was observed. The findings from each team were discussed to come to an agreed series of statements for each set of observations. These are the overarching findings from the research trip that cover user experience and attitudes towards sanitation in Kumasi, Ghana.

Reasons for acquisition of a Clean Team toilet

Importance of topic to the objective: Having an understanding of the reasons for a toilet to be acquired can inform the design of future technology to either enhance or supress features or aspects.

Summary of observations: The primary reason given for acquiring the Clean Team toilet service was down to convenience, and often it would be more specifically for the convenience of another member of the family such as an elderly relative. With 333 observations from the 18 hours of footage, the third most frequent observation was for the **collective.** The most frequently associated code with **Collective** was '*acquisition'*, so most of the time that respondents are talking about other members of the household, they are talking about the reason for investing in a toilet. Gender plays an important role in the decision making process, 74% of the time the decision maker is female, 21% male and the remaining 5% was simply unclear who was responsible for making the choice. However, it was common for the female to be the instigator but permission being sought from the husband. The majority had heard about it through friends or family. More information on the impact of poor sanitation on the females of Kumasi can be found in Appendix A.2.

Non-verbal communication

Importance of topic to the objective: As the subject of using toilets is one that can lead to embarrassment, the user's response may not be entirely honest or the full story. Ethnographic techniques can allow for interpretation by the observation team and the potential to identify hidden needs that the user would not realise themselves was an issue. Examples included: emotions, fear, humour and embarrassment. Using the consensus of the whole team reduced bias in the interpretation.

Summary of observations: A specific *fear* recorded in seven of the interviewees was that disease is transferred from the other people's faeces by what commonly referred to as 'heat' which is a concern for pit latrines. This indicates disease is widely misunderstood in the community. The belief that other people's excreta is the cause of disease is mitigated when using flushing toilets. The fear of other people's faeces spreading disease is also reduced when only the user and their family members use the toilet. *Pride* was coded on 52 occasions indicating the positive effect that a toilet can have on people's lives.

Use

Importance of topic to the objective: observing the respondents demonstrating how they would use the toilet allowed the researchers to investigate opportunities for design improvements that could be made or what aspects of the design have made the toilet easier to use (*e.g.* some users placing a stone in front of the toilet to raise the legs during defecation could indicate the toilet is not ergonomically optimal.)

Summary of observations: Of the 358 observations of use, the most frequent associated code was frustration suggesting that there are a number of ways for the user experience to be improved. The sight and smell of faeces was one cause for frustration and a reason that some people avoid using a public toilet. There was also a number of frustrations recorded in relation to the strength of the smell of the chemical used in some clean team toilets. Clean Team toilets that use sawdust also caused a number of frustrations such as being difficult for elderly to use or a cause of mess with children. In order to make the experience more comfortable, it was not uncommon to see a stone or similar object in front of the Clean Team toilet in order to raise the user's legs. According to the Clean Team representative facilitating the research, the method of cleansing after defecation was observed to be determined by religion. Christian responders will use toilet paper and Muslim respondents will wash with water. Due to ethical concerns questions relating to religion were not asked by the interviewers to confirm this statement.

Environmental surroundings

Importance of topic to the objective: It was important to comprehend how a new toilet technology would not only fit into the user's lives but also logistically in the home as some residents may not have had a household toilet before.

Observed: The common housing configuration was a large compound divided into several small dwellings surrounding a forecourt area. Such activities as cloth drying took place in the communal central area. Up to 40 people were reported as living in a compound. The Clean Team toilet was almost always located in one of two places; in an outhouse (n=20) where the old bucket latrine was formerly kept or in a ‘mori’ (n=16), (a tiled area of the house where washing took place specifically by Muslim residents). The link between faith and toilet location was the reason why out of the 106 observations of **culture**, the main code associated was to do with *physical layout*. Toilet paper could not be disposed of in the Clean Team toilet but it was also common in public toilets with flushing systems to still have a small bin next to the toilet for paper disposal so it would appear to be common practice not to dispose of paper in the toilet.

3.4 Toilets technology and example user

As Kumasi has a very limited number of toilets connected to the sewer network, there were a variety of alternative toilets in use by in use by its inhabitants. This section will now document the toilet variations encountered during the research in Kumasi and present each method or toilet alongside a person who could be seen as typical of the users of that toilet to present a toilet centred persona[10]. Personas are used to consolidate archetypal descriptions of users (Martin and Hanington, 2012) and a valuable tool in clarifying users during new product development (Lerouge et al., 2013). The two design team researchers discussed each technology and reached a consensus on who would be a suitable example for each technology, following the method of Lerouge et al (2013). The coded observations compiled during systematic observation were used to build each profile. Each persona is presented alongside the respondent’s attitudes towards their toilet and also considering barriers and enablers to make that person upgrade to an improved toilet. The toilet examples are presented in the same ascending order that was used in Objective One to review toilet technology. The

[10] All faces of interviewees have been obscured to protect identities in accordance with the consent form signed by each participant.

question “What factors could encourage the respondent upgrade their sanitation choice and practice?” was discussed by the two researchers based on the contextual understanding they had acquired throughout the deep dive process. The description of ‘upgrading’ was defined as the user choosing a better toilet practice or technology for the health of the user and for the local environment. These are the two factors that define improved toilet technology outlined by Kvarnström (2011) in the updated sanitation ladder. Additional comments made by the observation team were also recorded and presented for each profile to give added depth to the person. Images of the person and the example of the toilet they use (or example in the case of open defecation, chamber pot and shared flushing) are screen captures from the footage recorded by the researchers in Kumasi, Ghana.

3.4.1 Open defecation

Figure 21 – Open defecation persona. Respondent 03 and an example of his place of defecation[11]

Profile: Respondent 03	Young male

[11] The young male who practices open defecation was unable to take us to where he goes to the toilet so a photo taken nearby has been used to show what that area would typically look like.

Household	Four people in household. Him, mother and two sisters.
Respondent attitudes towards current toilet practice	Even though his mother pays for a Clean Team toilet in his home, he does not want to share the toilet with his mother and his siblings. He also said that he wouldn't use the public toilets because they are dirty and there are 'small maggots' there. Instead he prefers to openly defecate stating "big boys don't use Clean Team toilet" and he "finds a virgin space to go pee and more".
What are some of the barriers to adopting improved toilet technology?	He already has access to an improved method within his home but chooses not to use it. His personal beliefs around the practice of defecation is a major barrier. He also has a negative association with using public toilets due to them being poorly maintained.
What factors could encourage the respondent upgrade their sanitation choice and practice?	Changing the association with household toilets being used by women and the less-abled. Males of the community may be less at risk of attack but their excreta can be the cause of disease and an indirect danger to others. Behaviour change methods such as those employed by Community Lead Total Sanitation (CLTS) could help (Sah and Negussie, 2009). Toilets need to be a cause of pride and open defecation needs to be a cause of shame. Cleaner, more desirable public toilets will also encourage use.
Additional comments from the systematic observation team	This young man was slightly embarrassed to talk about the subject. He appeared keen to give the impression that he is a 'man' and wanted to show his independence from his mother and sisters even though openly defecating is arguably less convenient than using the toilet within the home.

3.4.2 Chamber pot

Figure 22 – Chamber pot persona. Respondent 66 and an example and a chamber pot[12]

Profile: Respondent 66	Elderly woman
Household	The elderly woman lives with a number of grandchildren, she doesn't specify the amount but says "many". The children range in age but most are under 12.
Respondent attitudes towards current toilet used	She used to use the public toilet but now uses a chamber pot because she's "weak" and the grandchildren empty it for her at the public toilet.
What are some of the barriers to adopting improved toilet technology?	Lack of mobility prevents her from using the public toilet. She had not heard of the Clean Team service but could see the value adopting the service. Her financial situation was not discussed but as she lacks mobility she will possibly be financially dependent on younger family members which could affect whether she can upgrade her toilet practice.

[12] The elderly woman was unable to show us the chamber pot that she uses so a photo taken in one of the other houses of a chamber pot has been used.

What factors could encourage the respondent upgrade their sanitation choice and practice?	The household toilet such as Clean Team toilet could improve her life and the lives of her grandchildren as they would no longer be responsible for emptying her excreta. As she rented, she would be unable to install a pit latrine due to the construction required. The flexibility of the Clean Team service would be compatible with people renting the homes from landlords as the toilet can be removed by the service person if circumstances change.
Additional comments from the systematic observation team	This is a sad situation that many elderly people in the community have to face. Chamber pots are not a dignified method of defecation and having to use one may also risk injury as the chamber pot will be unlikely to be secured. Losing independence and relying on children must be difficult to accept for the elder members of the community. As many Clean Team toilets were purchased for elderly relatives, specially adapted units incorporating handrails or a more stable base could make them easier and safer to use.

3.4.3 Public unimproved pit latrine

Figure 23 – Persona of a shared unimproved toilet. Shared Respondent 63 and the public toilet she uses

Profile: Respondent 63	Young female
Household	"About 20" within the compound.
Respondent attitudes towards current toilet used	Most of the compound use the public toilet and some of the children use a bag, they urinate in the wash area which is the outhouse. She doesn't like when "Squatting people miss the target and defecate around it" in the public toilet. She also says she can get 'caught short' when she has diarrhoea and has to run to the public toilet which can be embarrassing.
What are some of the barriers to adopting improved toilet technology?	She said it will be up to her mother to sign up for the Clean Team service but the males will have to be consulted. As there are 20 people within the compound the number of toilets would have to be considered.

What factors could encourage the respondent upgrade their sanitation choice and practice?	She stated a number of frustrations with her current method so she would be likely to be receptive of an improved option. She was aware of Clean Team because the service people walk through the area but she doesn't know anything more than that. Upon having the service explained, she said she would need more than one toilet as there's so many of them. They have an outhouse which is where they'd put it as she'd like privacy.
Additional comments by the systematic observation team	The user experience of the public toilet is highly unpleasant but also travelling to it can also be unpleasant if she is 'caught short' which was not something previously considered.

3.4.4 Public flushing toilet

Figure 24 - Respondent 27 and an example of the flushing toilet he used

Profile: Respondent 27	Elderly gentleman
Household	He lives with 15 people in a compound. Six in his house.
Respondent attitudes towards current toilet used	Used to use a private pit latrine but it became ‘spoiled’ 10 years ago because it was dug so deep ground water could come in so he now uses public flushing toilet. It’s now locked so no one can use it. He has the choice of two different local toilets, the one he uses is a four minute walk and has both sitting and squatting flush toilets. He prefers using the public toilet now though as it “is a flush and smells less” so he doesn’t worry about disease. He doesn’t like going at night “because you could meet robbers or thieves”. He had not heard of Clean Team before the interview.

What are some of the barriers to adopting improved toilet technology?	The user experience of the flushing toilet is important to him. A new household toilet would have to provide the good user experience.
What factors could encourage the respondent upgrade their sanitation choice and practice?	A household toilet that was as pleasant to use as a flushing toilet would mean he wouldn't risk attack at night and would still have a pleasant experience. A self-contained toilet such as Clean Team could potentially be located in the space where the pit latrine was located as seen in other households in the area.
Additional comments from the systematic observation team	He is still mobile and approximately aged in his early 60's, walking four minutes to the toilet is fine for him now but his mobility will likely reduce and walking to a public toilet will be more difficult. Perhaps, after a trial period he would value the convenience is worth the reduced user experience.

3.4.5 Private unimproved pit

Figure 25 - respondent 73 and her open pit latrine toilet

Profile: Respondent 73	Young female
Household	20 people with 6 people using the toilet
Respondent attitudes towards current toilet used	She is very proud of her toilet and maintains it well. She used to let others in the compound use the toilet but they wouldn't clean it so it caused arguments and they were banned from using it. One of the daughters cleans it every three days because she says 'Sometimes you can see faeces around the edge so you know it's not clean and by cleaning it every three days it stops smelling". They have a book of toilet paper at the back of the outhouse that they use for cleansing and then they put it in a plastic bin that is emptied every three days.
What are some of the barriers to adopting	The toilet is cast from concrete and would therefore not be easy to replace as doing so would require demolishing a substantial mould of concrete. As this is the only outhouse

improved toilet technology?	on the property it’s not obvious how a self-contained toilet such as the Clean Team can be used.
What factors could encourage the respondent upgrade their sanitation choice and practice?	Preventing insects coming in contact with excreta and travelling and back out again is very important to stop disease. If a Clean Team toilet is not suitable for them due to restricted space, improving this pit might be a quick and effective option. Mesh covering the ventilation pipe and a retro-fitted toilet pan such as the Sato pan by American Standard could prevent insect travel and reduce odour improving the user experience and household hygiene.
Additional comments by the systematic observation team	The toilet was all made from cast concrete so it would have been easy to clean possibly easing the hassle of cleaning and ensure the chore was done more regularly. This was a person who had enjoyed privacy of having her own toilet and was clearly very conscious of cleanliness and had strong views on the health implications that can come from poor sanitation. However, there was no mesh cover over the ventilation pipe at the back of the pit meaning flies could travel into the excreta and back out again which is a main way that disease spreads.

3.4.6 Clean Team bucket collection service

Figure 26 - Respondent 59 and her Clean Team toilet

Profile: Respondent 59	Mother
Number in household	8 people use the toilet, 6 kids from the ages of 6 – 15
Respondent attitudes towards current toilet used	She originally had the chemical toilet, then she was given the sawdust version as part of the trial but has now gone back to the chemical. This was because the kids create a mess with the sawdust and they also get urine in the bucket which causes a smell. She went on to say that if she was the only person using the toilet she would have kept the sawdust. The kids use the toilets at home rather than the flushing toilet at school. She believes the clean team toilet is beautiful. She invested in the clean team toilet through fear of contracting disease from the shared toilet she used to use, the disease was transferred by the heat. They use water to clean themselves after use so it's convenient that it's in the mori.

	16 other respondents mentioned the pride they had in their Clean Team toilet especially as some no longer have to use the unpleasant public toilets. The service is often talked about with great praise, such as the staff “being god”. There was a sense of trust in the service as the money and cartridge collectors would visit the same houses regularly and therefore and personal familiarity strengthened the brand image.
What are some of the barriers to adopting improved toilet technology?	Using sawdust rather than the chemical would be better environmentally but is difficult for the children to use correctly.
What factors could encourage the respondent upgrade their sanitation choice and practice?	She said she would be happy to use the Clean Team toilet with sawdust if it wasn’t for her kids having to use it and cause a mess. Sawdust can provide a good user experience if it is used correctly but with children this is uncertain. An improved Clean Team toilet that would dispense the sawdust into the container with the ease of a water flush could be a way to provide self-contained, compostable excreta with a good user experience suitable for children.
Systematic observation team	The Clean Team toilet has improved the lives of the family and gives them pride.

3.4.7 Private Flushing toilet

Figure 27 - Respondent 77 and the private flushing toilet she uses

Profile: Respondent 77	Elderly woman
Household	30 within large two-story compound.
Attitudes towards current toilet used	The woman talked with great pride about having a toilet and in particular it being a flushing toilet declaring “it makes me special”. She said that many people don’t have one so she likes to show it off. She said the children are privileged compared to others at their school. They have a bin next to the toilet for paper as they know they can’t flush paper. The lid is off the cistern because water in the area is unreliable and when the water is off they have to manually fill the tank by taking water from an outside large water tank.
What are some of the barriers to	From the user perspective, the flushing toilet is the best and cannot be surpassed. However, unreliable water supply

adopting improved toilet technology?	lead to frustration if they are unable to flush the toilet. A low-water flush toilet could improve this.
What factors could encourage the respondent upgrade their sanitation choice and practice?	An alternative toilet would have to provide the same level of pride and comfort which would be very difficult. Having to refill the water tank manually due to unreliable piped water is an inconvenience that they have accepted as being part of a flush toilet. Emphasising the financial benefit of not wasting water, as well as the improved convenience of not having to rely on irregular water access, could be encouraging factors.
Systematic observation team	This was a well organised household that was one of the more affluent of all those visited. She takes great pride in having a flushing toilet and believes it to be the best.

3.5 Summary of findings

Kumasi proved to be an immensely rich area for researching toilet user experience. The lack of sewer network and unreliable water meant the residents had diverse attitudes, behaviours and practices surrounding the act of relieving oneself. The diverse toilet practices allowed the researchers to observe and interview people from every level of the UN's sanitation ladder[13] (WHO, 2017). Seven distinct toilet practices were profiled ranging from the young male's resolute advocacy of defecating outside, to the pride an elderly woman has that her compound has a flushing toilet. Public toilets are mainly an undesirable but necessary part of life for many residents. The sight and smell of other people's

[13] The sanitation ladder is monitoring tool used by the UN to track sanitation progress by categorising users depending on the toilet they use (Satterthwaite and Mcgranahan, 2006).

faeces are a cause for disgust but the belief in 'heat' being a cause for disease was another frustration. As the Clean Team service was designed specifically for this community using deep consumer insight gathering techniques (IDEO.org, 2011), the toilet is well suited to meet the needs of many users. There were frustrations noted with the toilet itself but overall it has improved the lives of the users. Most of the non-users of Clean Team toilets interviewed hadn't adopted the service simply as they hadn't heard of the service. Of the seven user personas three were identified as potentially benefitting from the service (chamber pot, shared unimproved and shared flushing).

The Clean Team has made great progress and undoubtedly improved the lives of many of Kumasi's residents with latest report stating that over 500 households are being served (Greenland et al., 2016). This does however fall short of the ambitious target that they had for 30,000 toilets by the end of 2014 as declared in 2011 (Narracott and Norman, 2011). It is unclear what has prevented faster uptake but from this research, the service was highly sought after improving many lives in the community. Jenkins & Scott's (2005) model for adoption Figure 28 shows the decision pathway amongst people in developing countries for them to adopt improved sanitation. The model corresponds with the findings in Kumasi for adoption amongst Clean Team users. Clean Team users were dissatisfied with their current toilet practice (*e.g.* the unpleasant and inconvenient public toilet) and they became aware of the Clean Team service through a friend or neighbour. Due to the self-contained product there were no additional barriers that effect adoption that other toilet options would encounter (*e.g.* landlord disapproval of building a pit latrine) which gives the arrangement flexibility if circumstances change such as wealth or size of family.

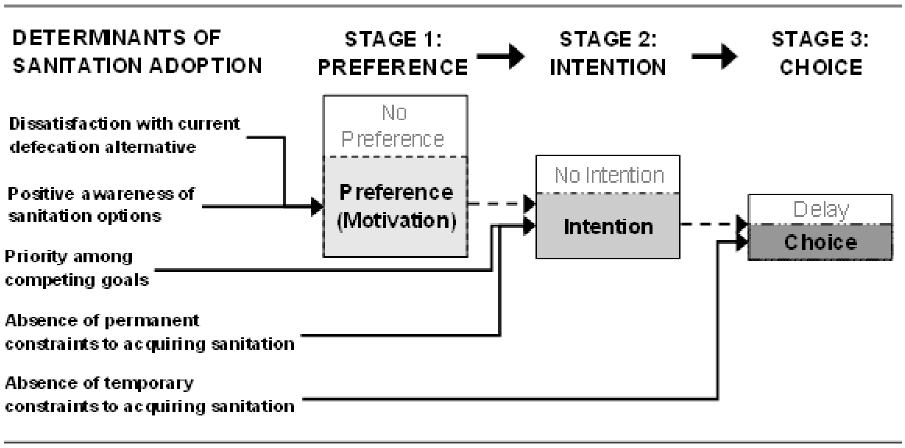


Figure 28 - Model of adoption and decision stages and determinants of new demand for sanitation (Jenkins & Scott, 2005)

3.6 Chapter analysis

Through the research conducted in this chapter, a rich understanding of the behaviour and attitudes of Kumasi residents towards toilet use has been formulated. This is a community that has poor sanitation coverage and is in need of better toilets solution to help alleviate the current sanitation issue. This understanding was found through the large amount of data that was captured through the semi-structured interviews that were conducted, based on the IBM-WASH model (Dreibelbis et al., 2013). Once this data was analysed, transferring contextual interviews into coded observations allowed a number of design recommendations to be made for an improved toilet system through seven toilet technology profiles. These key insights into the user experience, barriers and enablers to adoption, and the method of defecation are vital for informing the design of a new toilet technology to not only address the sanitation issue, but also to ensure consumer needs are met to encourage the adoption of an improved toilet solution.

3.6.1 Limitations

Researching such a personal topic is very challenging and has been noted as such by other researchers in particular the anthropologist Van Der Geest (2007) One limitation of researching this subject is not being able to truly observe someone in the act of defecating as this would be what true ethnographic research would be conducted. To circumvent this the researchers employed techniques such as asking the subjects to 'pretend as if they were teaching a child' and having them demonstrate without disrobing. Although this wasn't entirely accurate the researchers are confident in the method being a valuable approach to finding out about user attitudes to a sensitive subject.

3.7 Chapter Three highlights:

This chapter identified seven different toilets used in Kumasi and presented examples of the people who use them. The lack of access to sanitation clearly led to a number of issues for the household. People who had recently invested in the Clean Team toilet service felt a massive improvement to their life. There were, however, a number of frustrations identified with the Clean Team Toilet itself. The flushing toilet is considered the pinnacle of toilet technology whereas public toilets are a disliked but necessary part of life. Poor user experience was often caused by the sight or smell of other user's faeces and the perception of 'heat' caused a misunderstood fear of disease. The next chapter will examine key stages involved in the development and testing of a waterless user interface technology that could improve more than one of the toilets discussed already in Objective One and Two.

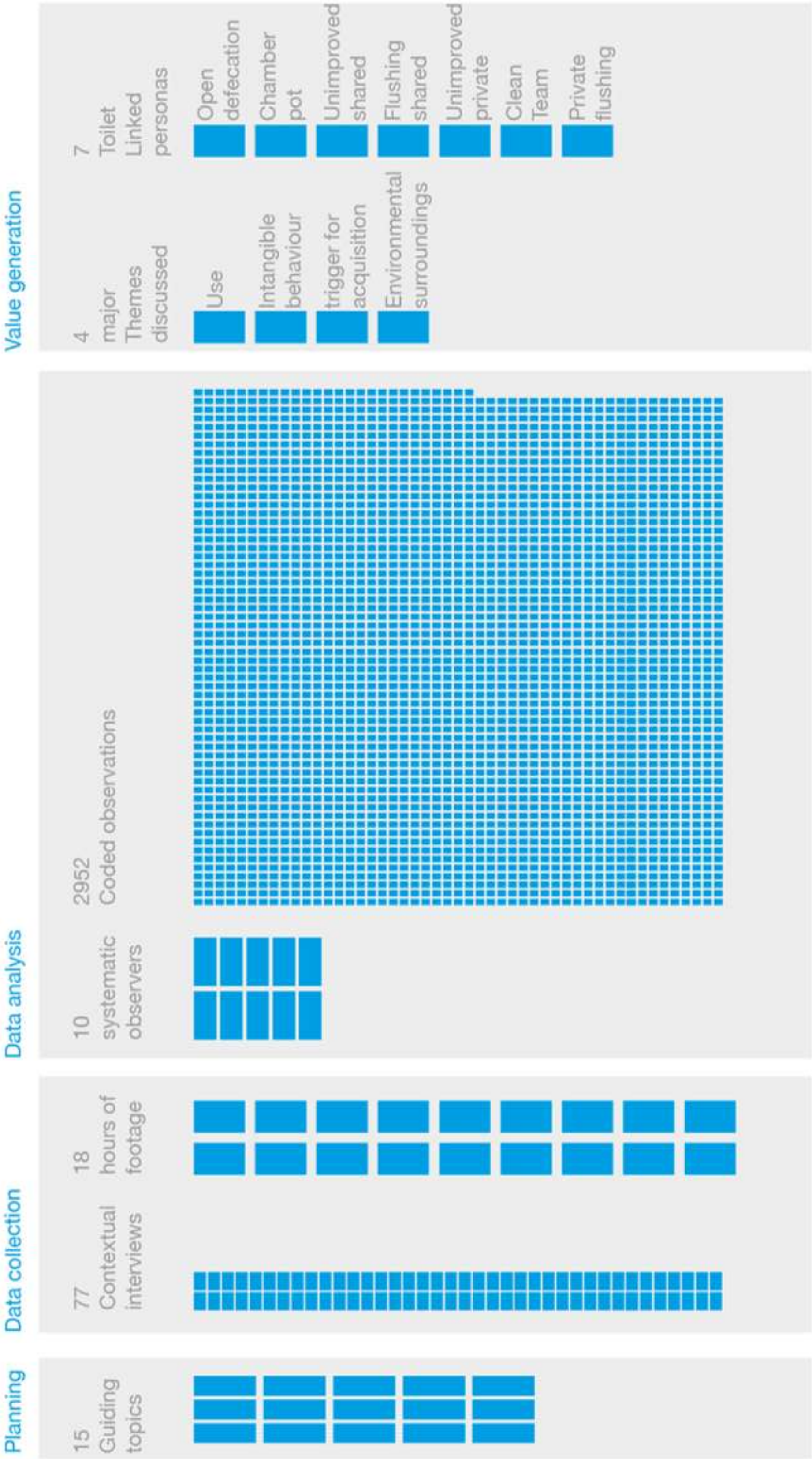


Figure 29 - Graphical overview of Chapter Three

“If a picture is worth a thousand words,
a prototype is worth a thousand pictures”

(Fredman, 2002)

4 DEVELOPMENT AND TESTING OF WATERLESS TOILET TECHNOLOGY

Objective Three: *To develop and prototype a technology to improve the user experience of a waterless toilet.*

This chapter documents the development and testing stages of a waterless toilet technology. The Rotating Waterless Flush (RWF) was specifically designed for the Nano Membrane Toilet (NMT) and will be the case study and driver of this research. The mechanism is designed to improve the user experience of the NMT whilst meeting the system requirements and taking the target market into consideration. This chapter is also intended to inform other designers and engineers on suitable methods and appropriate considerations for developing new waterless sanitation technology to stimulate innovation in a neglected field. Figure 30 shows the stages of this chapter that involve testing basic function, investigating new surface options and finally how the mechanism performs after multiple uses.

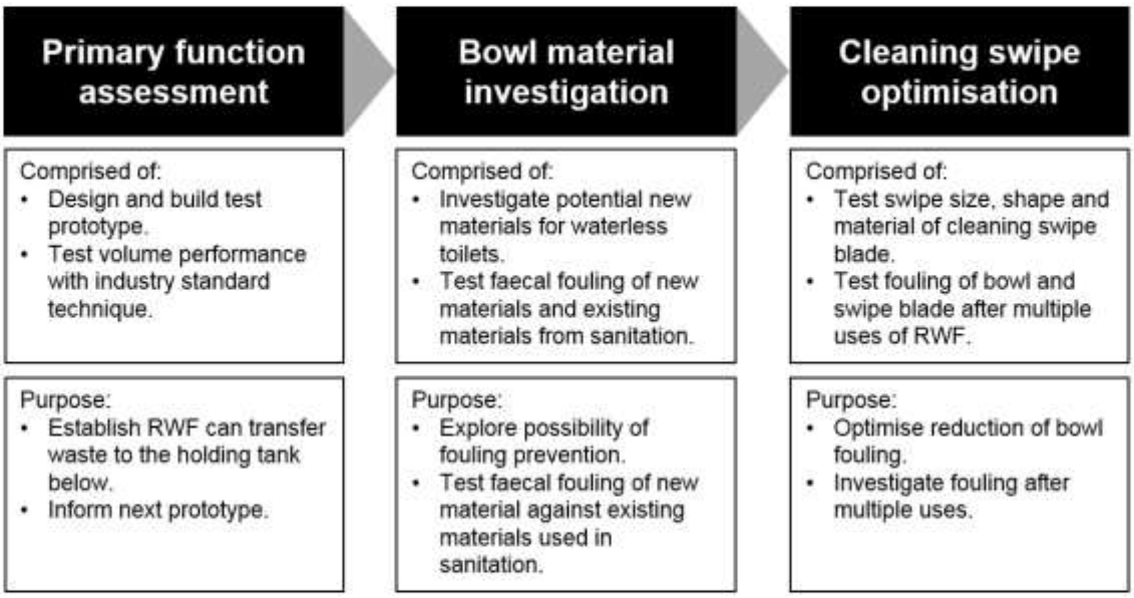


Figure 30 – Chapter structure with rationale of Objective Three

4.1 Background of the technology profiled

As part of the Reinvent the Toilet Challenge, funded by the Bill and Melinda Gates Foundation, Cranfield University moved into the third stage of development of a waterless toilet system in October 2014[14]. The proposed system works by combusting solid human waste into electricity and turns liquid human waste into clean pathogen-free water, through the use of hollow membrane fibres (see Figure 1) (Parker, 2014). To ensure the system is efficient, no additional water is to be used during the flushing process. This is opposed to flushing toilet systems currently used in much of the western world using up to 10 litres per flush (Narain, 2002) and has resulted in the design and development of the RWF. The technology transfers the user's excreta into a holding tank below before excreta processing can take place, whilst also limiting odour transfer. The RWF was first conceptualised as part of a Masters by Research project (Tierney, 2014) to minimise water use. The design brief can be found in Appendix A.4.

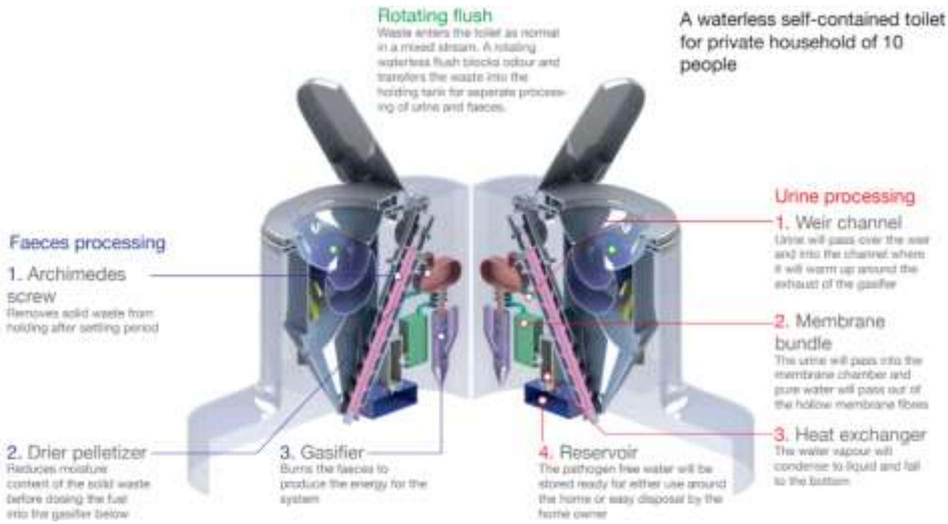


Figure 31 – Diagram explaining the Cranfield University Nano Membrane toilet and rotating flush mechanism identified with green. (Tierney, R. 2017)

---

[14] Full project description and toilet animation available at: http://www.nanomembranetoilet.org/

4.1.1 Research approach

To ensure structured progression along the innovation path, a Stage-Gate process was implemented ensuring deliverables were met during the testing and development phase. There has been discussion of ambiguity with the definition of innovation in literature (Crossan and Apaydin, 2010; Garcia and Calantone, 2002). A 1991 OECD study that has been regarded as best capturing the essence describes it as; “an iterative process initiated by the perception of a new market and/or new service opportunity for a technology-based invention which leads to development, production, and marketing tasks striving for the commercial success of the invention” (OECD, 1991). Using a Stage-Gate™ method ensured a robust structure to manage the innovation path (Cooper et al., 2002). Cooper, who has written extensively in this area, explains most ‘best-practice companies’ implement some form of idea-to-launch system such as Stage-Gate™ to improve likelihood of developing a successful innovation to take to market and beyond (Cooper, 2008). To evolve the rotating flush mechanism from a concept to being able to be used by a real person, prototyping and testing will require multiple steps and iterations. To ensure this is advancing in the correct direction ‘kill’ and ‘go’ points will be used (Cooper and Edgett, 2005). Three stages are the same as the stages shown in the chapter structure (Figure 30), comprising of various tests and an outcome deliverables that are discussed in more detail in the remainder of this chapter.

4.2 Stage 1: Primary function

To assess the rotating flush mechanism with regards to the basic function of transferring excreta into the holding tank below.

The basic function of the RWF concept is to transfer excreta from the user to the holding tank below. Assessing how well the RWF performed the function was a fundamental first step in the process. This required designing and building the first prototype to facilitate efficient and safe testing which will now be documented.

4.2.1 Preliminary prototype design

An early prototype produced during the Author's Masters by Research (Tierney, 2014) presented the waterless flush mechanism as a basic concept shown in Figure 32. This was a demonstration model to communicate how the concept involved a rotating bowl, driven by the user closing the lid with a cleaning swipe blade to clean the bowl. The demonstration model didn't take into consideration component size, volume performance (e.g. how much excreta could be transferred), cleaning performance or how the RWF would integrate as part of a multi-component system.

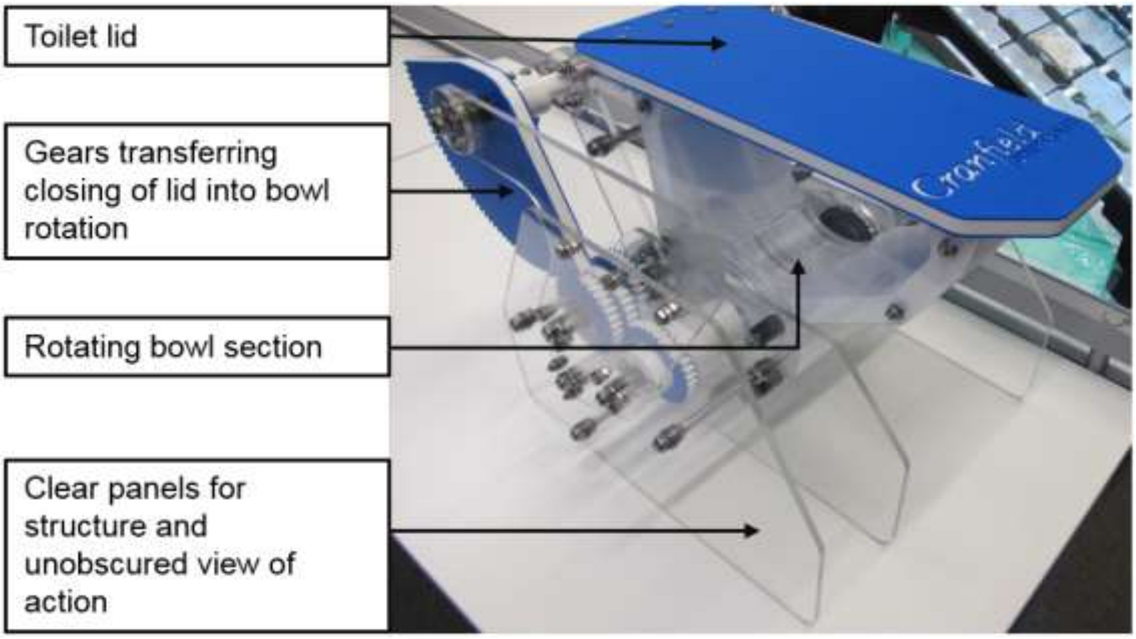


Figure 32 – Labelled photo of original Rotating Waterless Flush demonstration model from Masters by Research project (Tierney, R. 2014)

The first rotating waterless flush prototype (P1) of this phase of work was designed to test and measure the basic function of the mechanism. P1 was designed to be a simple construction that was easy to disassemble and assemble to improve efficiency of the development and testing stage. Being able to interchange parts easily would reduce time required for the development process especially as cleaning will be an important aspect due to risk of contamination when testing with real faeces. P1 is what Ullrich and Eppinger (2000) refer to as an *alpha* prototype as it allows for key tests to be conducted and to establish that the concept can satisfy basic function. When considering the NMT as a finished product, a toilet that would be easy to disassemble or change individual components would facilitate easier servicing and lower overall cost and waste (Lewandowski and Mateusz, 2016). The aim for the NMT is to give people a household toilet that is safe and pleasant to use. However, consideration has to be given to the other people involved along the journey of the product to ensure a successful innovation (Okurut, Kulabako and Chenoweth, 2015). These stakeholders include service people, distributors and manufacturers. Modularity could allow for maintenance to take place in a user’s home rather than the system being returned to a facility and therefore modularity was determined to be a consideration throughout the development. Simple sketches helped to quickly visualise, communicate and understand the modular P1 design as shown in Figure 33. The RWF was designed a modular case design comprised of three case parts and rubber seals.

.

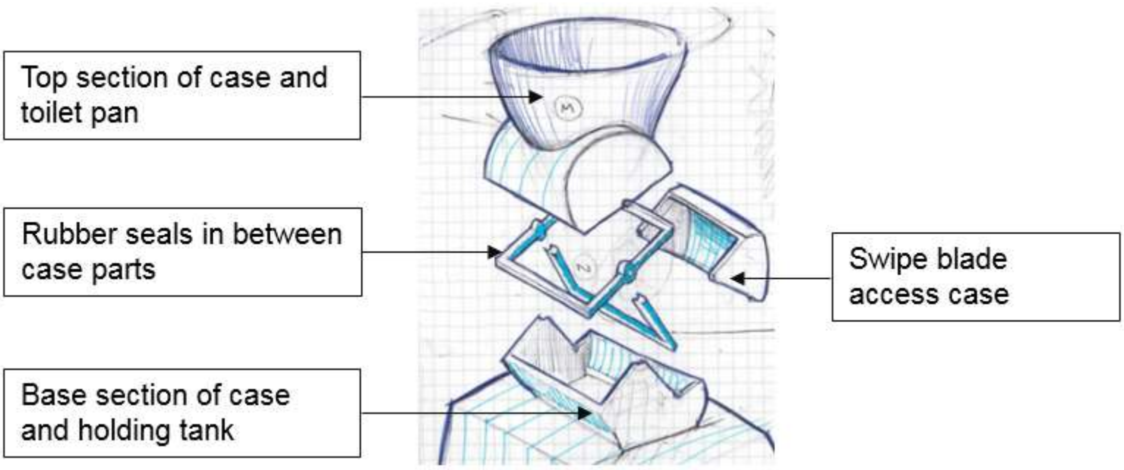


Figure 33 - Earliest sketch of modular flush mechanism test rig

A common mantra of product development is to ‘fail fast, fail cheap’ (Hall, 2007) or “fail fast, fail often” (Asghar, 2014). Having this type of mind-set in the early stages helps to ensure the best solution is attained through multiple, rapid iterations. Low-level prototyping with cardboard allows designers to move from 2-dimensional sketches to 3-dimensional objects quickly and with little cost to progress the idea. The cardboard prototype (Figure 34) was used during a concept workshop by a consortium of experts including designers and engineers from the NMT project and an external advisor. The concept was discussed and the prototype design refined before a final design for fabrication was produced and agreed upon.

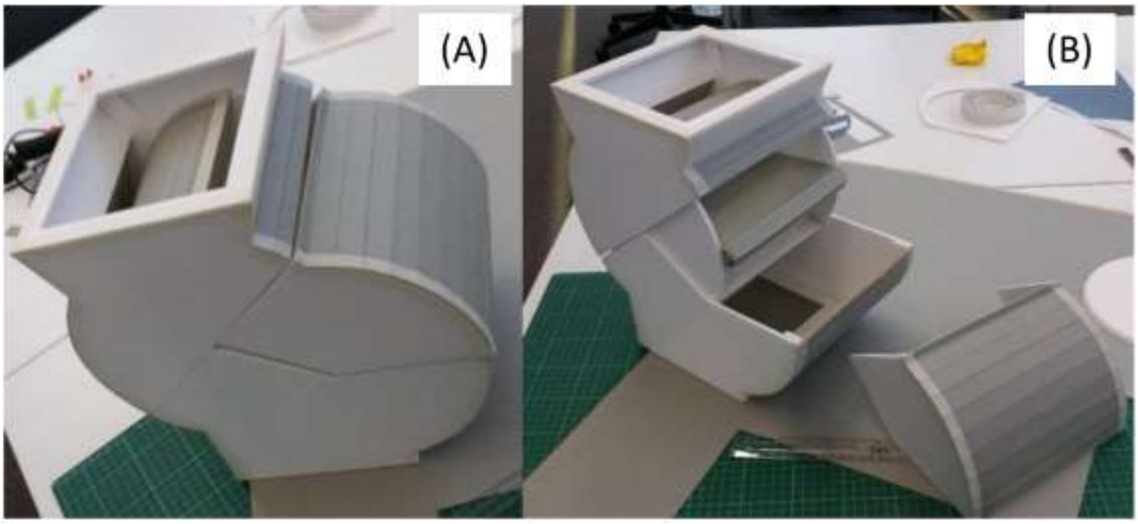


Figure 34 – Photos of low-level prototyping with cardboard. (A) Complete prototype (B) Experimenting with modularity and access to key components such as swipe blade. (Tierney, R. 2017)

A final test for the cardboard prototype was evaluating the shape and size within a skeletal frame of the complete toilet. Giving consideration to how a component integrates within the complete system and especially the parts immediately impacted by it, are incredibly important during the development phase. In this case it was important to ensure there was a suitable distance from the user to the bowl and that the RWF would allow for a suitable depth of the holding tank below.

Figure 35 – Integration testing with cardboard modular prototype inside aluminium skeletal toilet frame with red outline for clarity. (Tierney, R. 2017)

Following the consortium workshop, the flush prototype was redesigned to be simpler and cheaper utilising a combination of 3D-printed nylon by selective laser sintering (SLS) and Laser cut Perspex. 3D-printing or additive manufacture as it is also known, refers to a group of technologies that build Computer Aided Design (CAD) models, layer-by-layer into three dimensional objects (Marcus, Beaman and Crawford, 1994). SLS printing builds three-dimensional parts layer-by-layer from CAD files by targeting a laser beam to fuse powdered nylon together with an accuracy of 150 microns (Laughlin, 2011; Thompson, 2007). Other 3D-printing such as fuse deposition modelling (FDM) were available and generally cheaper with regards to both material and equipment but the finish is of a lower quality (Stratasys, 2016). SLS is regarded as producing the smoothest curved pieces which would be important for the inside of the bowl of the RWF. Laser cutting sheet acrylic is the quickest way to get to accurately produce two-dimensional parts and using this process for the side walls of P1 not only allows the sides to be clear acrylic but also reduces time and cost. Using the CAD program SolidWorks, 2D and 3D files can be produced for use on the different machinery (Figure 36). Figure 36 also shows how the CAD model was designed in such a way to reduce the cost of SLS printing by 'nesting' parts internally.

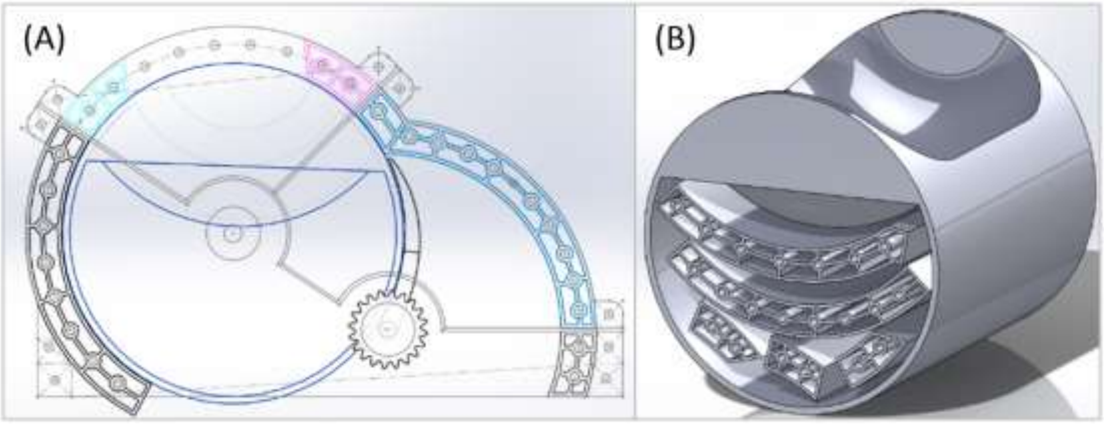


Figure 36 – CAD models of P1. (A) 2D CAD design of prototype. (B) 3D CAD model of prototype for printing SLS printing with ‘nested’ internally to reduce printing volume and cost. (Tierney, R. 2017)

The design of the prototype works to the strengths of the different processes and materials as well as using standard components (M5 bolts and 5mm threaded steel rod) to complete the assembly. P1 allows for quick changing of components and easy cleaning after tests both showed the importance of these attributes to save time during development and testing phase. Certain elements from the original RWF demonstration model were continued such as the clear walls for easy viewing.

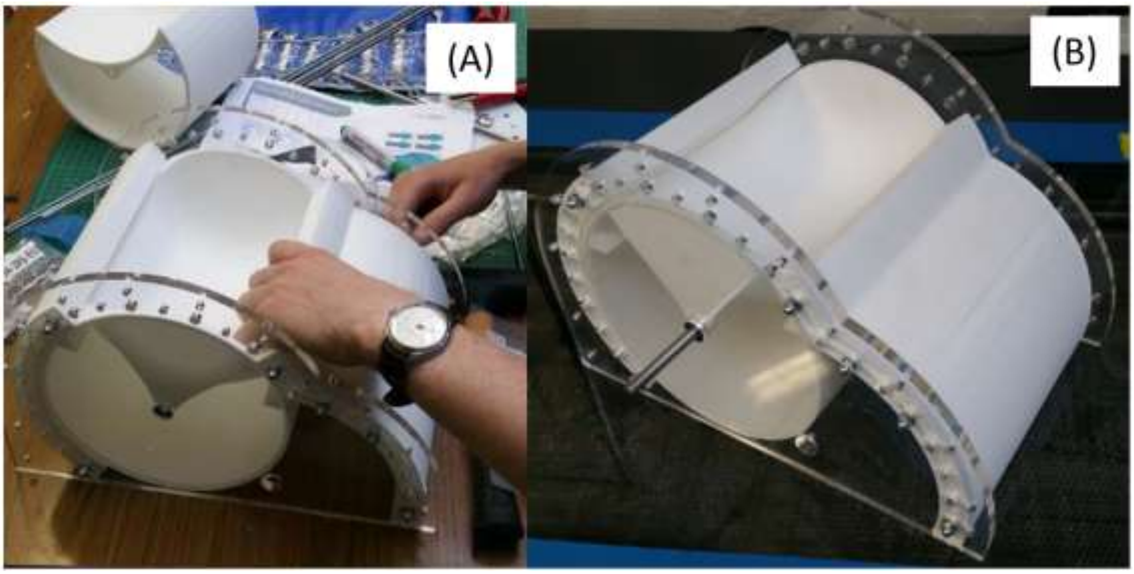


Figure 37 – (A) Assembling P1 from laser cut Perspex side panels and SLS nylon printed body. (B) Complete P1 for volume and exit point testing. (Tierney, R. 2017)

The modular architecture of P1 allowed multiple variations to be tested easily. A second configuration was produced utilising the modular aspect allowing a cross-section (70% cut) of the entire model. The cross-section allowed the movement of the faeces during the rotation to be observed from the side. This was important for the development of the RWF to asses any design improvements required for effective performance. SLS nylon has a porous quality and would be absorb any liquid becoming fouled and unhygienic very quickly (Marcus, Beaman and Crawford, 1994). To mitigate this risk and also make cleaning easier, the outside of each nylon part was tightly wrapped in a thin plastic film and secured with adhesive tape.

4.2.2 Testing basic performance requirements

The industry standard test for assessing flushing toilets is called the Maximum Performance (MaP), introduced by a water engineer Bill Gauley in 2002. There is no definitive testing procedure for a waterless toilet and therefore the MaP test will be used to benchmark performance of the RWF. The method uses soybean paste moulded into consistent shape and size cylinders dropped from the same height and location into the toilet bowl. Each test increases the amounts into a toilet in 50g intervals before flushing. A blockage is regarded as a failure and would establish the rating for the toilet. Figure 38 shows the official MaP test results scale and categorises the performance according to the amount flushed ranging from not recommended to highly recommended, passing 600g is seen as a 'premium toilet' (Gauley, 2016a). Soybean paste is also used during testing by TOTO Ltd[15], one of the world's largest toilet manufacturers, due to the similar water content and density to real faeces (George, 2008). Other simulant faeces been developed (Radford et al., 2015; Wignarajah et al., 2006) but being able to buy soybean paste readymade makes testing much easier. The MaP test has a

[15] TOTO Ltd were founded in Japan in 1917 with current annual sales of over $5 billion USD (TOTO, 2014). Their global website is http://www.toto.com/

minimum acceptable pass amount of 250g in one flush which is a significantly larger amount than the 128g an average person passes per day (Rose et al., 2015).

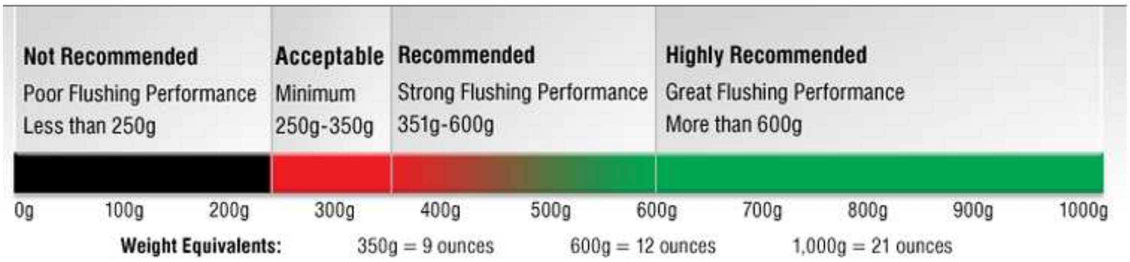


Figure 38 – MaP test performance indicator showing toilets unable to flush 200g classed as 'not recommended' and toilets able to flush 600g and above 'highly recommended (Gauley, 2016a)

The MaP test is the industry standard for flushing toilets and therefore a new 'failure point' had to be determined for non-flushing toilets. To test the rotating flush mechanism by MaP standards, the point of failure was decided to be when the soybean paste would get trapped during rotation as shown in Figure 39. Faeces hitting the pan of the toilet that doesn't rotate would be an issue as it would cause undesirable fouling.

Figure 39– (A) 750g of soybean paste in the bowl of P1 (B) 750g of soybean paste at the point of failing the MaP test

All measurements for testing were recorded with A&N GF2000 digital scales with an error margin of ±0.05g and calibrated before use with 1g, 10g, 50g and 100g weights. The soy bean paste was loaded in 50g intervals starting at 100g, and each test was repeated three times to improve reliability. Each rotation would drop the soy bean paste onto cling film to measure how much soy bean paste had been transferred. The results can be seen in Table 8. The one failure at 200g was unexpected as the next few tests passed all three times. The results of the MaP test were presented to the full team working on the project and discussed concluding that although the rotating flush performs very well, the one failure at 200g is a concern for reliability. Considering the MaP test is the industry standard for testing water based toilets, the component needs to be perform well against this measure.

Table 8 – Average results after three MaP test results

Weight in (g)	Transferred from bowl into container below (g)	Weight of soybean paste remaining in bowl (g)	Number of successful passes
100.00	99.5	0.5	3
150.00	149.6	0.4	3
200.00	199.9	0.1	2
250.00	249.7	0.3	3
300.00	299.8	0.2	3
350.00	349.5	0.5	3
400.00	399.6	0.4	2
450.00	448.7	1.3	3
500.00	498.3	1.7	2
550.00	549.6	0.4	3
600.00	596.1	3.9	1
650.00	629.2	20.8	0
700.00	648.1	51.9	1
750.00	693.4	56.6	0
800.00	772.0	28.0	0

(green)	3 pass
(yellow)	2 pass
(orange)	1 pass
(red)	0 pass

4.2.3 Testing with real faeces

Although soybean paste is convenient and easier to use, testing with real faeces is essential to accurately assess the performance of the RWF. Faeces samples were anonymously donated using disposable faeces collection containers left in a designated toilet, in the same building as faecal testing was going to take place (more detailed explanation about the Health and Safety protocol and practical issues of real faeces and simulant faeces can be found in Appendix A.3. Four samples were tested and the average weight was 125.46g, close to the average amount per day of one person according to Rose *et.al* (2015) of 128g. Faeces is categorised by consistency into the seven points of the Bristol Stool Chart (BSC).

BSC1 is described as being small hard pieces that can be indicative of constipation and BSC7 is described as being watery liquid. The classification is widely used by medical staff and in clinical practice to visually assess patient intestinal transit (Lewis and Heaton, 1997). The two researchers conducting testing with the RWF agreed upon the classification for the each samples. The average solid content of the samples was 20.32% which is just under the 25% average solid content found by Rose *et.al* (2015). These samples were individually dropped into the bowl prototype and rotated to test if a normal defecation would pass through the mechanism with results shown in Table 9. Testing with real donated faeces is more difficult the soybean paste which can just be picked up and dropped in. For this test, a disposable spatula was used to empty each of the faecal sample containers into the bowl to limit risk of faecal contamination. As shown in Table 9, all faeces samples passed through the prototype and into the tank below.

Table 9 – Testing the rotating flush with real faeces

Sample	Type (BSC)	Mass (g)	% Solids	Pass/Fail
1	3	119.5	25.9	Pass
2	6	154.7	15.2	Pass
3	6	186.7	20.0	Pass
4	6	40.82	20.2	Pass

The regular configuration prototype was used to begin with, followed by the cross-section configuration of the prototype to observe how the faeces would leave the bowl as shown in Figure 40.

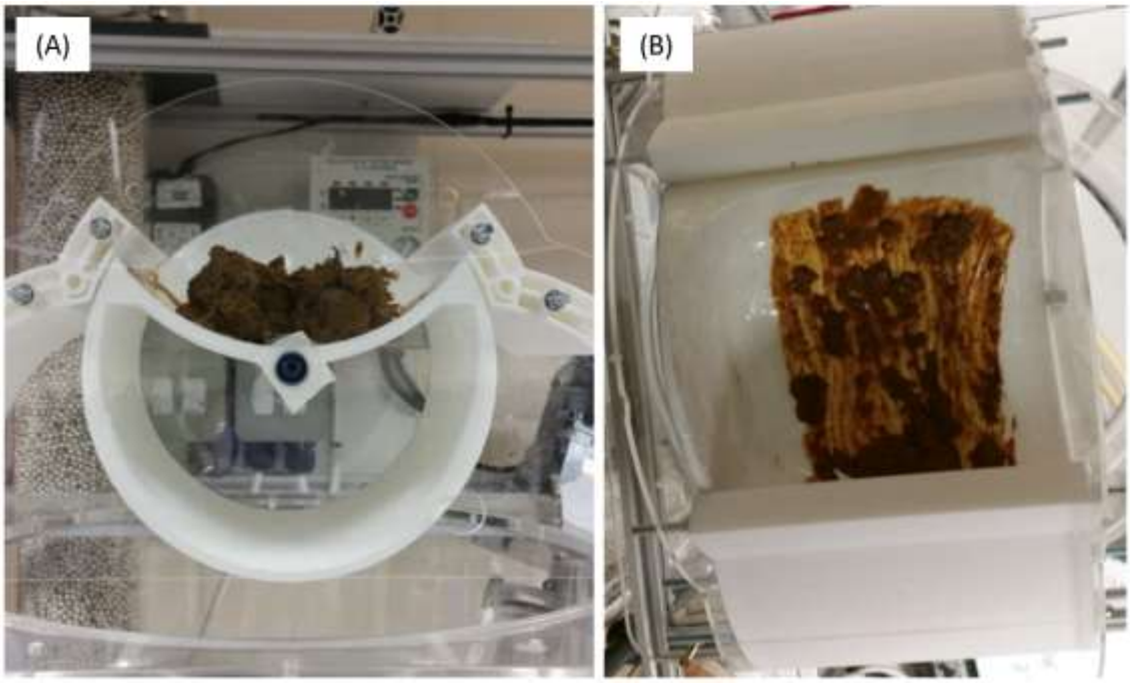


Figure 40 – Testing faeces sample number 3. (A) View through cross section prototype of sample in bowl before rotation. (B) View from above cross section prototype after rotation showing severe faecal fouling. (Tierney, R. 2017)

4.2.4 MaP test with real faeces

To gain a better understanding of how the bowl would deal with larger faecal loads, a set of tests similar to the MaP test were conducted. Nine donated faeces samples were combined and mixed to give a homogenised mass before being measured into increasing amounts and dropped into the middle of the bowl. Previous testing had shown that small amounts would pass through the RWF easily so testing began at 150g and increased in intervals of 100g. The test was repeated three times and each of the three sets used a new batch homogenised faece samples. The faeces that remained in the bowl after each test was left until the end to see how the faeces would accumulate and what dropped below was weighed and recorded. Out of all 21 tests there was only one failure that occurred at 750g.

Table 10 – Map test with real faeces. Averaged from three sets of tests

Weight in	Average weight dropped below	Amount remaining in bowl	Number of successful passes
150	131.8	18.2	3
250	210.2	39.8	3
350	319.9	30.1	3
450	466.5	-16.5	3
550	549.4	0.6	3
650	642.6	7.4	3
750	693.1	56.9	2

(green)	3 pass
(yellow)	2 pass
(orange)	1 pass
(red)	0 pass

Testing with real faeces has benefit of gaining understanding of the component under real performance but the disadvantage of being less standardised. One example of this is the soy bean paste cylinders can be dropped into the bowl with greater ease than a homogenised mass of real faeces that had to be emptied with disposable spatula.

4.2.5 Cumulative rotation test

To ascertain how repeated use would accumulate in the bowl, 150g of real faeces was loaded into the flush mechanism 20 times in a row and rotated after each load. 150g was chosen to be slightly heavier than the normal amount a person would produce.

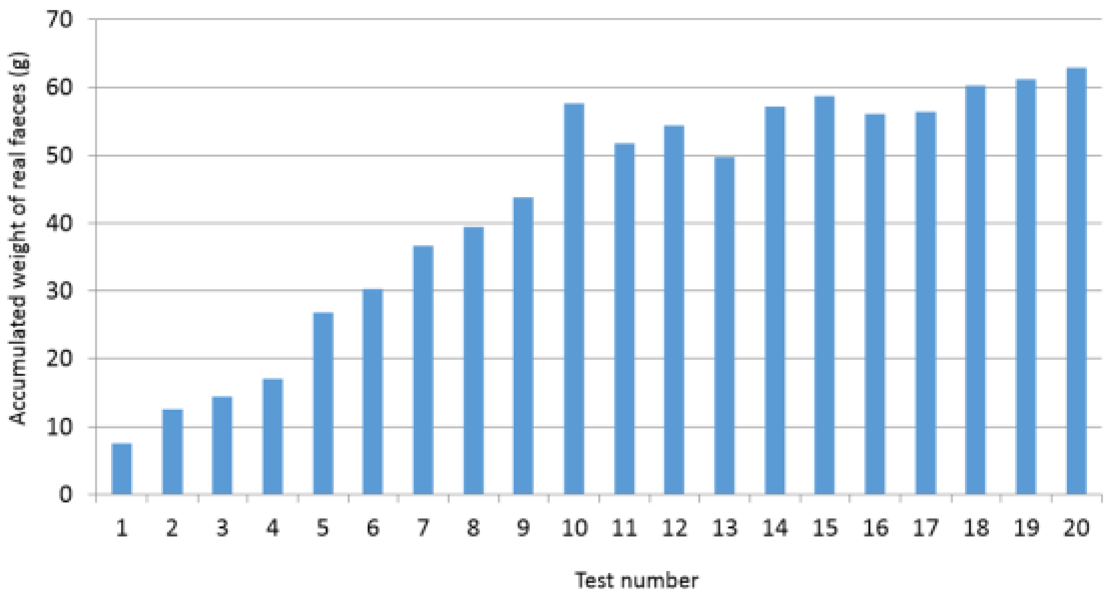


Figure 41 – Graph showing accumulation of faeces on bowl after 20 uses.

After 20 rotations over 60g of faeces had accumulated in the rotating bowl. Fouling of the rotating bowl surface would likely cause an unpleasant user experience confirming the need for an additional cleaning method for the bowl.

4.2.6 P2 bowl testing

A senior design engineer rebuilt the original CAD model and incorporated a simplified driving mechanism for the RWF and a power storage method using a spring for the Archimedes screw. As basic function had been tested, the improved CAD design was built considering the manufacture of the part as well as the function (Figure 42).

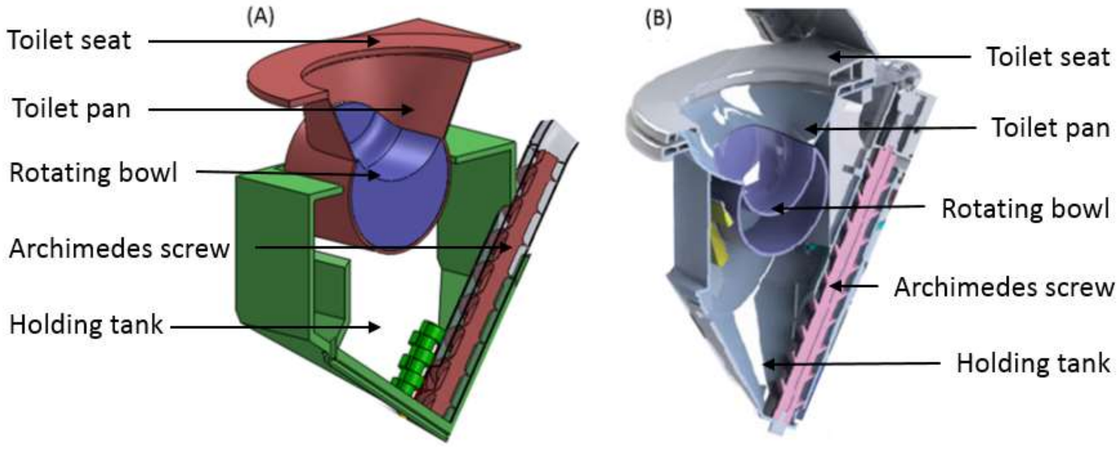


Figure 42 – (A) Original CAD model (B) Refined CAD model of user interface by senior design engineer (Tierney, R. 2017)

The second major prototype (P2) (Figure 43) of the user interface incorporated the bowl with the increased depth and will be manufactured using a different method. P1 was SLS printed and spray painted whereas P2 will be SLS printed and then vacuum cast in polyurethane with no additional finish. Due to project demands, an identical second prototype was required for demonstrations and therefore casting was the more cost effective method of producing two models. This process uses a vacuum to draw polyurethane into a mold made from the SLS printed rotating bowl and a different mold for pan that acts as a master (pattern). Vacuum casting ensures there will be no porosity or imperfections in the newly produced rotating bowls and pans as well as being low cost and ideal for low batch runs (Thompson, 2007). Ulrich and Eppinger (2000) referred to this type of prototype as a *beta* prototype as it allows for more extensive testing that is closer to intended real-world use. P2 will also include the holding tank and Archimedes screw to allow for the first testing of how the faeces would settle in the holding tank. A metal support frame will be incorporated capable of withstanding user testing.

Figure 43 – Photo of user interface of P2 for testing swipe performance with metal support frame. (Tierney, R. 2017)

To assess the performance of P2 with the redesigned bowl, the MaP test was conducted again. The rotating bowl of P2 out-performed the P1 with the first failure recorded at 650g. This is 50g greater than what quantifies a premium toilet according to the official MaP test (Gauley, 2016b).

Table 11 – MaP testing with P2 Bowl depth

Weight in	Number of successful passes
100.00	3
150.00	3
200.00	3
250.00	3
300.00	3
350.00	3
400.00	3
450.00	3
500.00	3
550.00	3
600.00	3
650.00	3
700.00	2
750.00	2
800.00	2

(green)	3 pass
(yellow)	2 pass
(orange)	1 pass
(red)	0 pass

The MaP test was developed as faeces is the main cause of blockage in a flushing toilet, whereas liquid will just flow over the S-trap into the sewer. Testing with simulated urine and soybean paste also showed the benefit of the deeper bowl. By adding 200ml of water to simulate the average urine produced per toilet visit and then adding 50g of soybean paste in increments P1 was almost at the point of overflowing with 500g of Soybean paste. P2 However, could contain that amount with considerable room remaining as shown in Figure 44.

Figure 44 – Testing both prototypes (A) P1 (B) P2 with 500g of soybean paste and 200ml of water to simulate urine. (Tierney, R. 2017)

4.2.7 Summary of stage 1 and recommendations

The RWF has evolved from a demonstration model to testing prototype. The volume performance of the rotating bowl was tested using the MaP test, the industry standard method as well as real human faeces. The rotating bowl of P1 recorded a failure at 200g which was a cause for concern to the wider team. To address this concern, the bowl depth of the next prototype was increase by 10mm and the walls were raised as the addition of urine was another concern raised during testing (Figure 45).

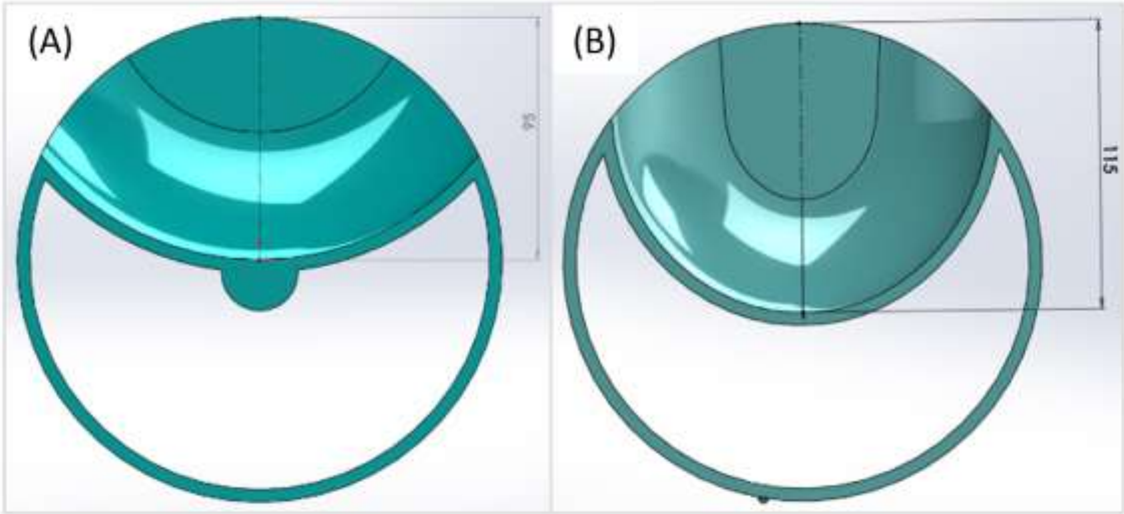


Figure 45 – (A) Cross section of the original bowl P1 (B) Cross section of P2 showing the bowl depth increase. (Tierney, R. 2017)

Additional testing was conducted to gain a better understanding of how the RWF would empty the excreta into the holding tank below. These results were presented to the wider NMT team to inform engineers of where the excreta would be expected to land in the tank and how that could affect the Archimedes screw. A more detailed explanation of this can be found in Appendix A.5.

Recommendations

- Soybean paste for use as simulant faeces in future tests due to its similarities to real faeces and use in industry.
- Accumulation testing confirms need for cleaning swipe blade.

4.3 Stage 2: Preventing faecal fouling

To identify the optimal surface for use in waterless toilets

After testing the basic function of the rotating flush to meet the system needs, the testing and development could now look to improving the user experience. P2 will use a polyurethane bowl due to low cost and ease of manufacture but testing alternative materials was determined to be a valuable task by the design team. This testing could not only inform future prototypes but also other waterless toilet user interfaces as very little research has been conducted on faecal fouling. The sight of other people's faeces is a major frustration noted in the literature (Keraita et al., 2013) and primary research in Kumasi, Ghana. One respondent said "I used a public toilet when I had an upset stomach and I didn't like what I saw…people miss the target and defecate around it". In an article by National Geographic on the sanitation crisis they interview a woman who declares "dirty squat plates" as one of the reasons the public toilets are universally reviled (Royte, 2017). The unpleasant sight of surface fouling is unfortunately highly likely in toilets that do not have water to clean the surface after use. Faeces remaining on the surface will also produce increased odour, another prominent frustration of toilet users (Chappuis et al., 2016). A pleasant user experience over a poor user experience is defined as *'relative advantage'* one of the five characteristics identified by Rogers (2010) as leading to adoption.

4.3.1 Clean toilets

Toilet cleaning is a billion dollar industry with one product alone Domestos, totalling over $250 million in sales across 50 countries (De Sousa and Marcos, 2016). Preventing surface fouling from occurring in the first place would be a huge selling point for new toilets and prevent a lot of the frustration of using public toilets (Sugden, 2014). One of the largest toilet companies in the world TOTO Ltd, released a high-tech toilet called the 'NEOREST AC' in 2015 that claims to automatically self-clean after each use. The toilet senses a user approaching, raises the toilet seat and sprays a pre-mist of electrolysed water called 'ewater' that has antibacterial properties. After defecation, the user flushes the toilet with ewater and the lid closes, activating a UV light inside the toilet bowl that reacts with the toilet surface and the ewater. This reaction causes the breakdown of organic substances on the surface and the cleaning of a fouled bowl (Belussi and Orsi, 2015; Szczygiel, 2016). Although this is a promising technology and encouraging to see that there is research and development in this area, the NEOREST AC retails for approximately $9,000, prohibitively expensive to all but the world's richest people. The toilet also relies on a considerable amount of water for each flush as well as electricity to power the various technologies. Preventing or cleaning fouling without water will be a considerable challenge but one with huge benefit.

Before studying how a complex substance like faeces could be repelled without water, the first step will be to explore the basics of repellency. Hydrophobicity is the well-known material attribute of water repellency, whereby water doesn't 'wet' the material's surface. Figure 46 shows the difference in appearance of a wetted surface (a) and a non-wetted surface (b). When a liquid is placed on a solid surface the behaviour of the liquid depends on the *relative* surface energy of the liquid compared to the surface energy of the solid (Carter and Norton, 2013). If there are adhesive forces, the liquid will spread across the surface as shown in Figure 46 (c). Cohesive forces within the liquid will cause the liquid to bead up and avoid contact with the surface (d) (Datta and Mukherjee, 2016). The contact angle of the liquid to the surface is the foremost measure of wetting, if a liquid has a low contact angle such as Figure 46 (e) there is adhesion unlike a higher contact angle shown in (f). Roll-off angle is another indicator of repellency. The minimum inclination required for a droplet to roll off the surface is recorded, with a high roll-off angle demonstrating adhesion (g) and a low roll-off angle demonstrating repellency (h) (Parkin and Palgrave, 2005). Superhydrophobicity is defined by two criteria; a high water contact angle (>150°) and a very low roll-off angle (<5°) which are normally caused by a specific combination of two properties; first surface roughness and secondly low surface energy(Balu, Breedveld and Hess, 2008; Wong et al., 2011; Yu, Zhao and Zheng, 2007). Between 2016 and 2023 the total revenue of hydrophobic materials is forecast to increase by nearly a factor of 15. This increase is from $194 million in 2016 to $2.8 billion in 2023 with the construction industry seeing the largest growth (Wang and Ondrey, 2016).

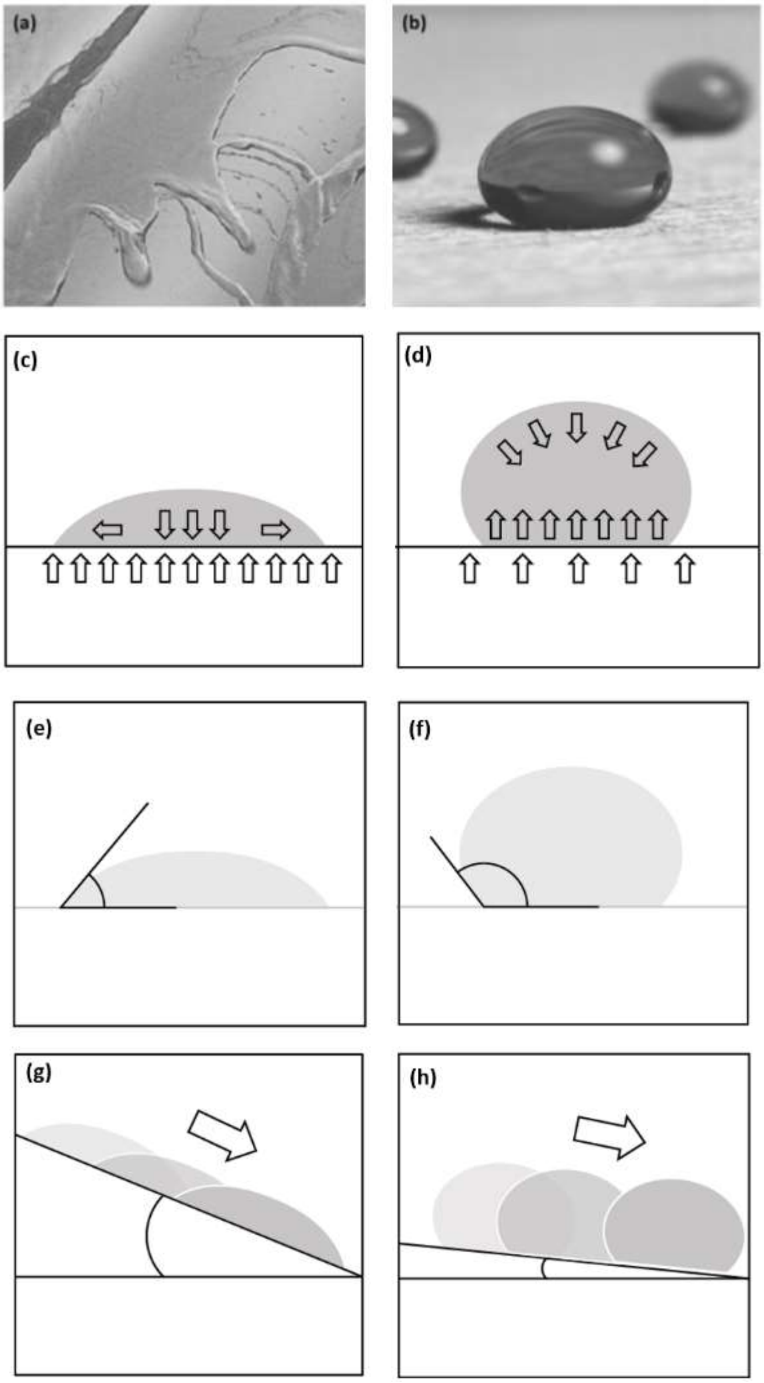


Figure 46 – Example of (a) liquid wetting a surface due to adhesive forces, (b) liquid beading on surface due to cohesive forces (Datta & Mukherjee 2016). (c) Liquid wetting surface due to high surface energy of the surface relative to the liquid causing adhesion (d) Solid with low surface energy causing liquid beading due to cohesive forces (e) Acute (small) contact angle due to surface wetting (f) large contact angle of non-wetting (g) large angle required for 'roll-off' (h) Small 'roll-off' angle.

Superhydrophobicity can be a desirable attribute in the natural world and the leaves of many plants, most notably the Lotus flower (*Nelumbo nucifera*), display natural Superhydrophobicity (Bhushan 2010). This repellency affords self-cleaning, whereby dirt particles are collected and removed as rainwater rolls off of the leaf (Marmur, 2004). Materials mimicking the properties of these specialist leaves have been developed since the 1970's such as household paints that can be cleaned with a spray of water (Beylerian, Dent and Quinn, 2007). Wilhelm Barthlott of the University of Bonn is credited with discovering the Lotus effect and the early material development after noticing certain plants wouldn't need cleaning when he was capturing their surface with an electron scanning microscope (Forbes 2008).

When considering the Lotus Effect for the surfaces of the RWF or any other toilet, the difficulty in repellency is due to faeces viscoelastic nature and wide variety of compounds within each defecation. Faeces can be classified into seven classes that make up the Bristol Stool Chart (BSC), from solid pellets (type1) to watery liquid (type 7) (Lewis and Heaton, 1997). Faeces can be described as a viscoelastic substance as it can exhibit both solid-like and liquid-like behaviour (Lentle and Janssen, 2011) and the adhesion of such viscoelastic solids is characterised by the Dahlquist criterion. When viscoelastic solids below a certain value of approximately 0.3 Mpa[16] come in contact with a surface, the substance will adhere to the surface by forming conformal contact. Most surfaces are to a degree 'rough' and adhesion of viscoelastic solids is increased as the roughness of the surface increases due to there being more surface area for the substance to conform to (Packham, 2003). Viscosity of faeces is generally determined by the diet and health of the person as this affects the moisture content of the faeces, higher moisture content is associated with lower viscosity faeces (Woolley et al., 2014). However, oily agents such as indigestible sucrose esters of fatty acids can soften the stool but also alter the relative surface energy between the faeces and

---

[16] Mega pascal (MPa) is the unit of measure for modulus of elasticity that ranges from 0MPa to 1Mpa (Osakue, 2013)

the toilet surface (Lentle and Janssen, 2011). Liquids with a lower surface tension than water, such as oils and ethyl alcohols will not have the sufficient cohesive force to bead and will wet the surface (Bhushan, Jung and Koch, 2009). Surfaces that repel oils are referred to as ‘oleophobic’ and surfaces that have an affinity to oil are referred to as ‘oleophilic’ in the same way that attaching the suffix ‘philic’ to ‘hydro’ indicates a surface that will attract water. Amphiphobicity is the repellency of both water and oils and omniphobicity is the repellency of everything meaning oils, water and low-surface tension liquids (Gogolides, Ellinas and Tserepi, 2015). Omniphobicity is rare in the natural world but one known example is Springtail (*collembola*) which have a complex hierarchical surface that combine nanostructure and microstructure to prevent wetting even from low surface tension liquids as shown in

Figure 48 (a, b & c) (Hensel, Neinhuis and Werner, 2016).

Omniphobic surfaces are relatively new to material science with recent progress encouraged by advancements in nanotechnology. Various surfaces and manufacturing techniques are being researched by a few highly respected institutions such as Harvard University, Pennsylvania State University and University College London (Wang and Ondrey, 2016). Since 2009, when research on Omniphobic surfaces was first published, there has been a constant increase in the number of associated publications, from three journal articles in 2010 compared to 29 in 2016. As these surfaces are still in early development, it was only possible to test one surface currently being developed at Pennsylvania State University. Slippery Liquid Infused Porous Surface (SLIPS) was inspired by the edge of the Pitcher plant (*nepenthes*) (Figure 47) and uses a porous microstructure substrate imbibed with a lubricant. This ensures substances that come in contact with the surface are actually only in contact with the lubricant and not the substrate (

Figure 48 d) (Wong et al., 2011). The consistency of the lubricant determines the performance and there is a trade-off between longevity of lubricant against performance of lubricant. A light (less viscous) lubricant would repel foreign substances well but would not last as long as more viscous lubricants according to the development team.

Figure 47 – Pitcher plant (Nepenthes). Image source Encyclopaedia Britannica (Britannica, 2017)

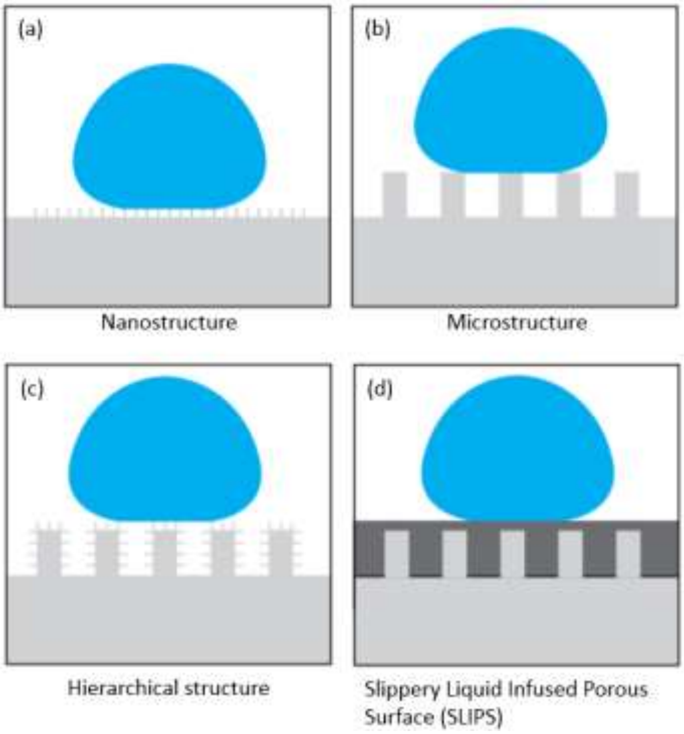


Figure 48 – Variations in surface structure of non-wetting surfaces. Illustration adapted from Hensel *et. al*. (2016) (a) Nano structure (b) Microstructure (c) Hierarchical structure (d) Slippery Liquid Infused Porous Surface (SLIPS)

Preliminary testing of the repellency of the first samples of SLIPS involved apparatus holding the surface at a 45° angle above a collection container covered with paper towel. Donated faeces samples were dropped from above using a disposable spatula to dose the faeces and direct the sample on to the test material. The preliminary testing with SLIPS used an aluminium substrate and the lubricant ‘Krytox 101’ which was the lightest grade of Krytox lubricants suitable for the process. Krytox is a perfluoropolyalklether, a form of Perfluorinated carbon (PFC) meaning it’s a synthetic oil made of carbon (21.6%), oxygen (9.4%) and fluorine (69.0%) (duPont, 2012). The first set of aluminium and Krytox 101 tests with real faeces was not successful as there was clear fouling as shown in **Figure 49**. A titanium substrate was also tested with similar results.

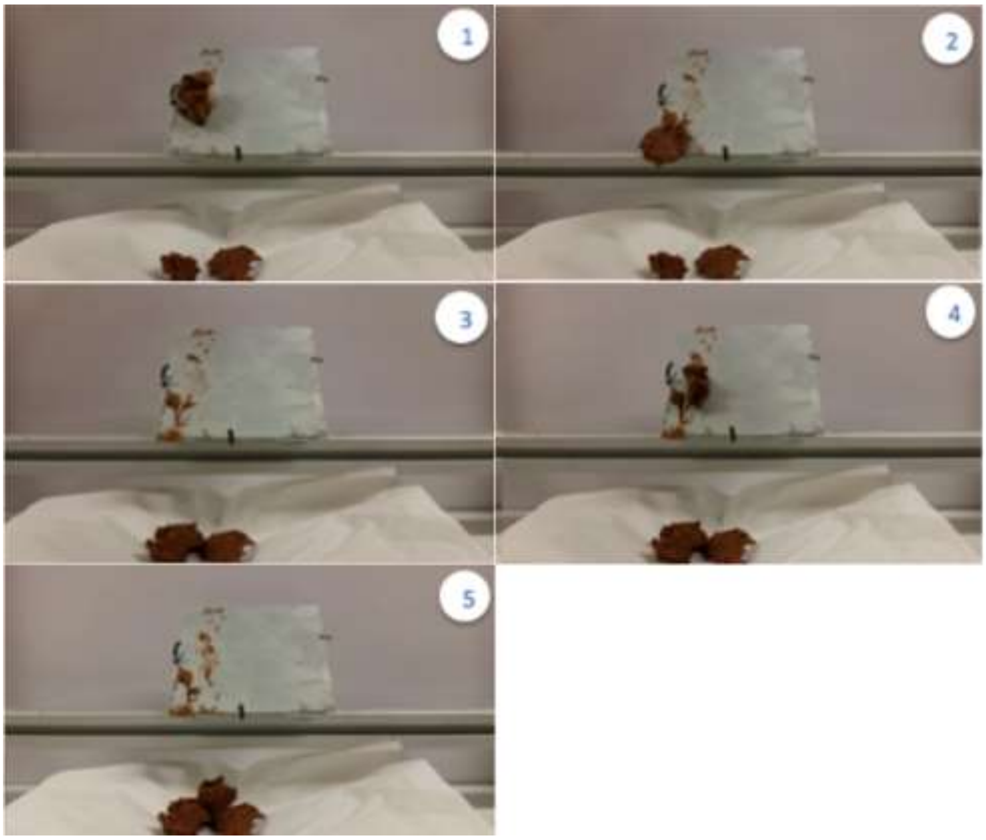


Figure 49 – Sequence of images from testing SLIPS Aluminium surface with Krytox 101 tested with real faeces shown in sequence after five samples were dropped onto SLIPS test surface

Subsequent development by Pennsylvania State University used silicone oil as the lubricant instead of Krytox and a special ceramic instead of aluminium. Preliminary testing with soybean paste was promising with soybean paste rolling-off the surface easily (Figure 50). This test was repeated with a UV trace fluid mixed with the Soybean paste to identify any residue remaining on the surface. Under UV light, no remaining residue could be observed indicating complete repellency.

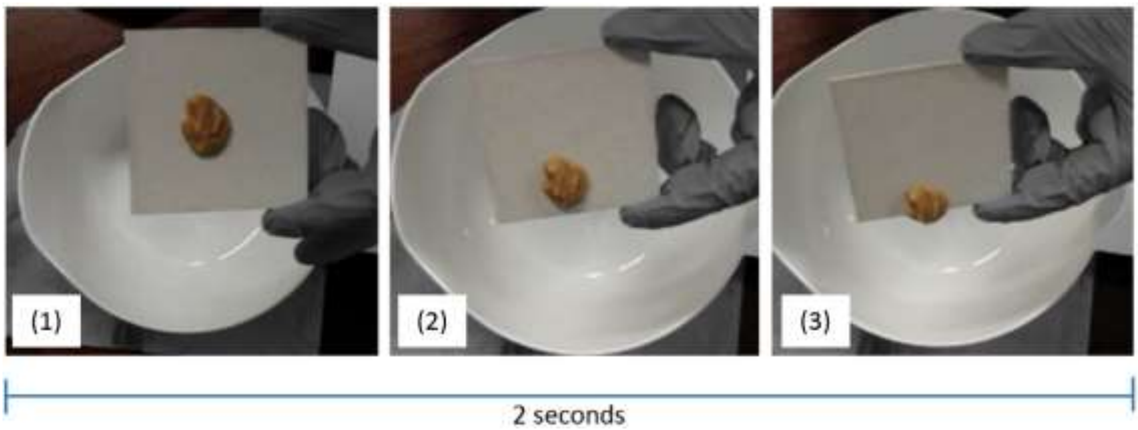


Figure 50 – Sequence of photos of Soybean paste rolling off of SLIPS imbibed with silicone oil in two seconds as filmed from above. (Tierney, R. 2017)

To test the fouling of various materials with real faeces, testing apparatus was designed and manufactured that would allow for a consistent amount of sample faeces to drop onto a test surface below (Figure 51). Once on the surface a holding pin on the side is removed causing the test material to drop from a horizontal position to a vertical position and the faeces is expected to slide off leaving a fouled surface behind. The faeces sample was homogenised mix of three donated stools that would be loaded into the faeces template which was a circle cut into the top piece of acrylic. The diameter of the hole was 36mm and as the acrylic was 8mm thick, the volume of faeces was 8143mm^3. A second piece of acrylic could slide back and forth underneath the template to release the faeces to fall below. The COSHH assessment for surface testing can be found in Appendix A.7.

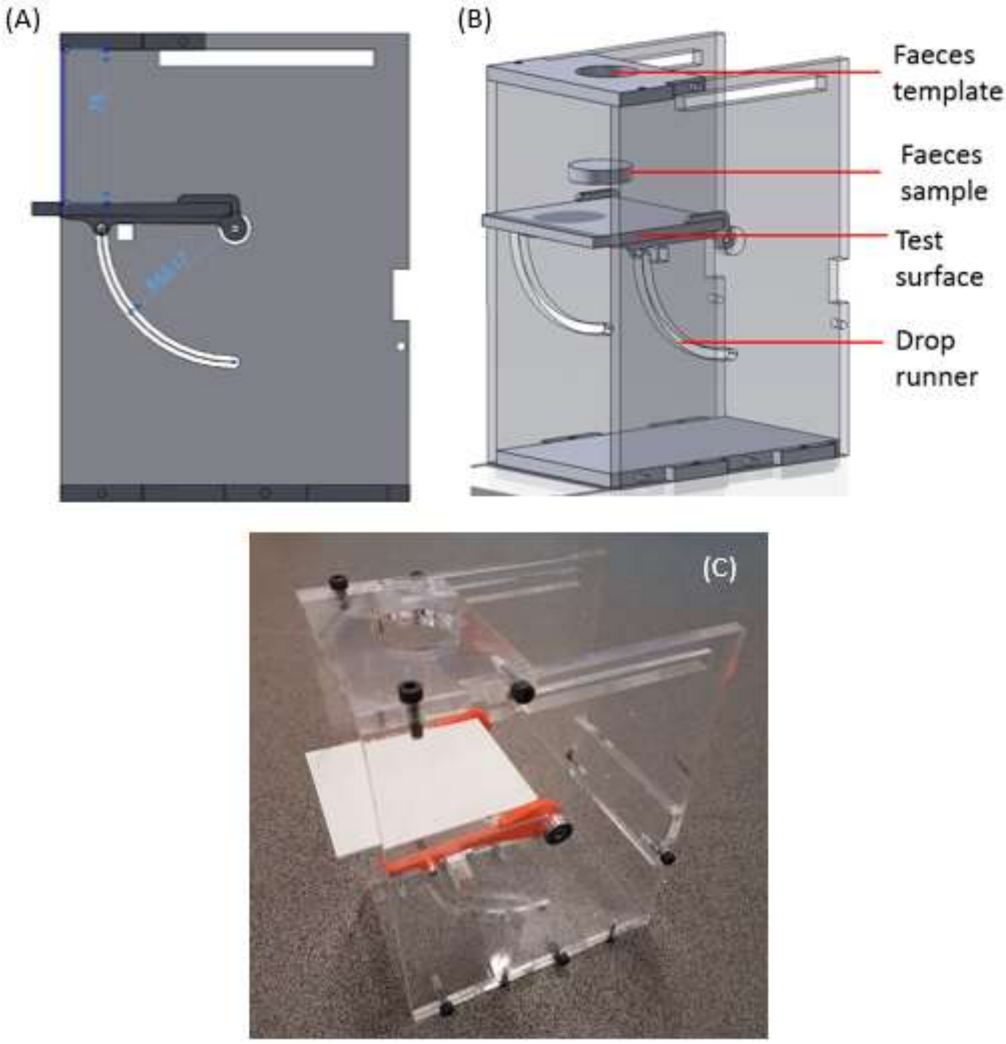


Figure 51 – Images of 'Drop rig' testing apparatus that measures and drops set amount of faeces onto test surface below, that is held horizontal until a holding pin is removed and the test surface drops to a vertical position (A) Side view of CAD model (B) Labelled CAD model (C) Photo of drop rig. (Tierney, R. 2017)

4.3.2 Identifying existing surfaces for comparison

Research in literature has not investigated the faecal repellency of materials for use in toilets. Reports for construction of simple sanitation options focus on safe construction rather than improving the user experience (Practical Action, 2004; Seleman and Bhat, 2016). To begin this research, a shortlist of various material options were compiled. ‘A collection of contemporary toilet designs’ by WEDC and EOOS (2014) is a valuable resource profiling a wide range of toilets in use around the world and was used as a starting point for researching different materials used. Three materials were selected for comparison against SLIPS that have different qualities and applications within existing toilets and one extra material that was identified from literature.

Acrylonitrile butadiene styrene

The Sato pan is an example of a low-cost plastic toilet pan that can be added on top of pit latrines[17] to improve the user experience (Curtis, 2016). The plastic used for the Sato pan is acrylonitrile butadiene styrene (ABS) primarily because it is inexpensive and has excellent toughness as it has the highest impact resistance of all polymers. It can also be processed easily, have good chemical resistance as well as a high-gloss finish, all desirable attributes for use in toilets (Kulich et al., 2001).

Ceramic

Western flushing toilets are traditionally made from a special clay mix called vitreous china. A three- stage process is required, first air-drying the special clay to harden the form, then fired (baked) in a kiln and then fired for a second time with an enamel glaze coating (Georgilas and Tourassis, 2007). Glazed ceramic relies on either the water to clean the surface and/or a toilet brush to remove

[17] A basic toilet waterless toilet profiled in Objective One

faecal fouling. Ceramic is a common material for toilets because it can be manufactured easily and is pleasant for the user. A complete toilet including outlet pipe can be cast in one piece that is fired with a waterproof glaze producing a high-quality product able to take the weight of a user and cleaned easily (Thompson, 2007).

Polytetrafluoroethylene

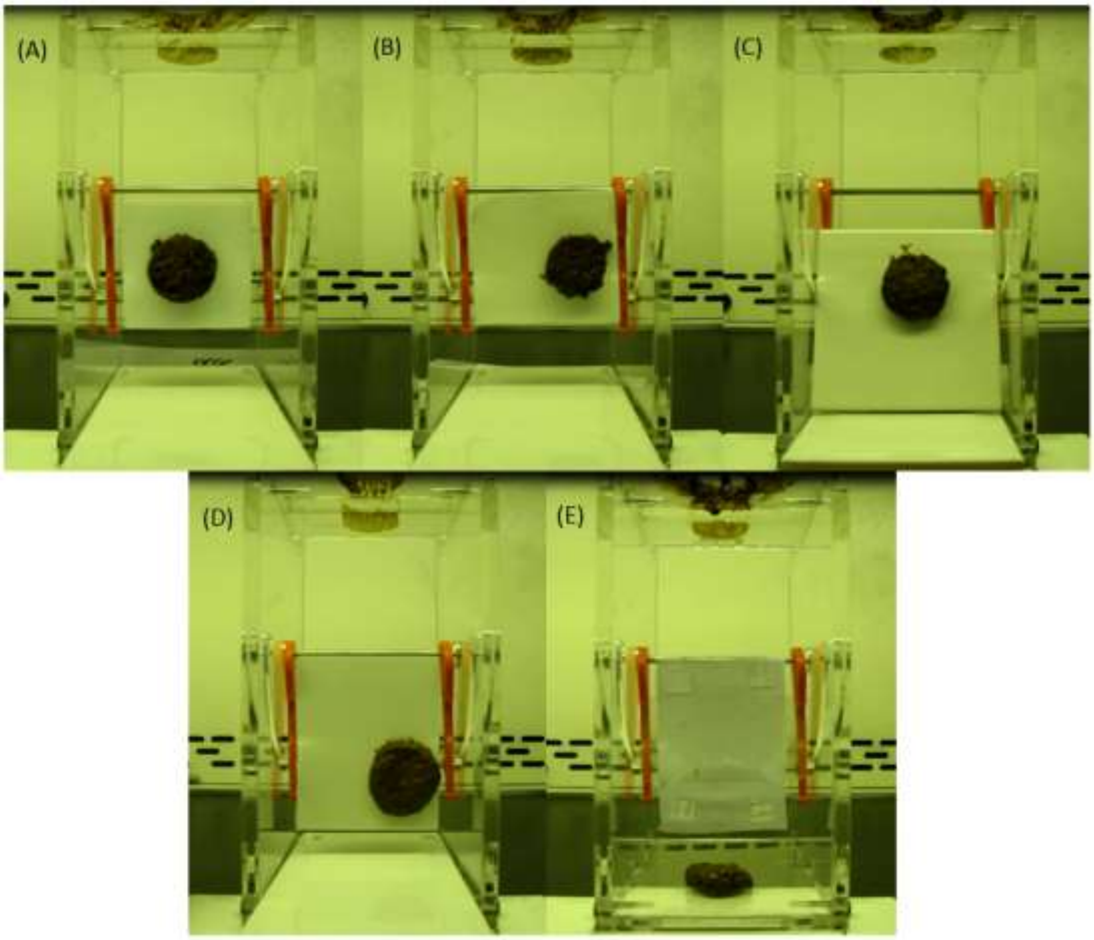
Polytetrafluoroethylene (PTFE) is used in some low-water toilets such as vacuum assisted toilets on trains and aeroplanes due to its low-friction/non-stick surface measured at 18.5mN/m (3M, 2015). It's a widely used in commercial and domestic applications and account for 90% of all fluoroplastics produced worldwide. PTFE is regarded as the benchmark low surface energy material but has limitations due to its oil repellency and due to its high melting point it is difficult to injection mold (Ashby and Johnson, 2013; Tsibouklis and Nevell, 2003).

Silicone

After investigating other low-surface energy materials, silicone was identified as a material of interest as it has a relatively low surface energy of 24 mN/m (compared with nylon for example that has a surface energy of 43mN/m). Silicone is a widely produced material for such uses such as cookware and medical apparatus due to the flexible soft form, heat resistance and low chemical reactivity. Silicone is also resistant to bio-fouling and can also be engineered to display antibacterial properties indicating it could be very practical for uses in sanitation (3M, 2015; Callow and Fletcher, 1994; Tang et al., 2011).

4.3.3 Testing surfaces with real faeces

The planned test for the first drop rig test was to load the faeces sample in the template (cut out hole) on the top of the drop rig then slide back the piece of acrylic under the faeces so that it would drop onto the test surface below. However, the faeces just stayed in place and adhering to the edges of the hole, it was released using a micro spatula. When the support pin on the side was removed, the test surface dropped from a horizontal position to a vertical position and the faeces was expected to slide down the face of the surface. The size of the faecal fouling that remained was measured using the software *ImageJ*[18]. As shown in Figure 52, for the first four surfaces (PTFE, Silicone, glazed ceramic and ABS) the faeces didn't move at all. The faeces were cleaned off the surface using another piece of silicone leaving a fouled surface. The SLIPs with silicone oil repelled the faeces and it slid leaving no residue behind. After repeating the test twice more, a small amount of fouling could be observed on closer inspection.



[19]

[18] ImageJ is the regarded in the scientific community as being at the forefront of image processing and analysis software for the past 25 years and still receives ~7000 website visitors per day (Schneider, Rasband and Eliceiri, 2012).
[19] This image and results from this test are used in the article 'Design of liquid and solid repellent coatings for extreme water—saving (Wang, J. Sun, N. Tierney, R. Corsettia, M. Lic, H. Wang, L. Wong, Williams, L. Wong, P-K. Wong, T-S.) Submitted to 'Nature Communications'.

Figure 52 – Photographs after faeces has dropped onto surface and surface drops to vertical position (A) Faeces stuck to PTFE (B) Faeces stuck to Silicone C) Faeces stuck to ceramic D) Faeces stuck to ABS (E) Faeces having fallen off of the surface once it had been dropped to the vertical position without leaving any residue on the SLIPs surface.

Only glass with silicone oil did not foul. It is also worth noting that contact angle does not indicate performance against faecal fouling as silicone has the highest contact angle and still fouled. PTFE is synonymous with 'non-stick' characteristics and was expected to perform better than other surfaces but this was not the case. Testing the surfaces with three different faeces samples resulted in considerable fouling to all but SLIPS.

Repeated testing of SLIPS with real faeces shows the limitations to performance. The surface was used four times during the testing in Figure 52 and was then cleaned with deionized water until no faecal fouling was visible to the naked eye. The surface was clearly displaying hydrophobic qualities as water would bead and roll off quickly. When no water particles remained, silicone oil was reapplied and allowed to imbibe into the surface. As with previous testing, the surface left in a vertical position for approximately 10 minutes to ensure there was not an excessive amount of oil on the surface before being loaded onto the drop testing apparatus. A micro-spatula was used to dose a smaller amount of homogenized faeces onto the surface below before the holding pin was removed and the surface fell to a vertical position. The time taken for the faeces to fall off of SLIPS was recorded as well as the accumulation of faeces (Figure 53).

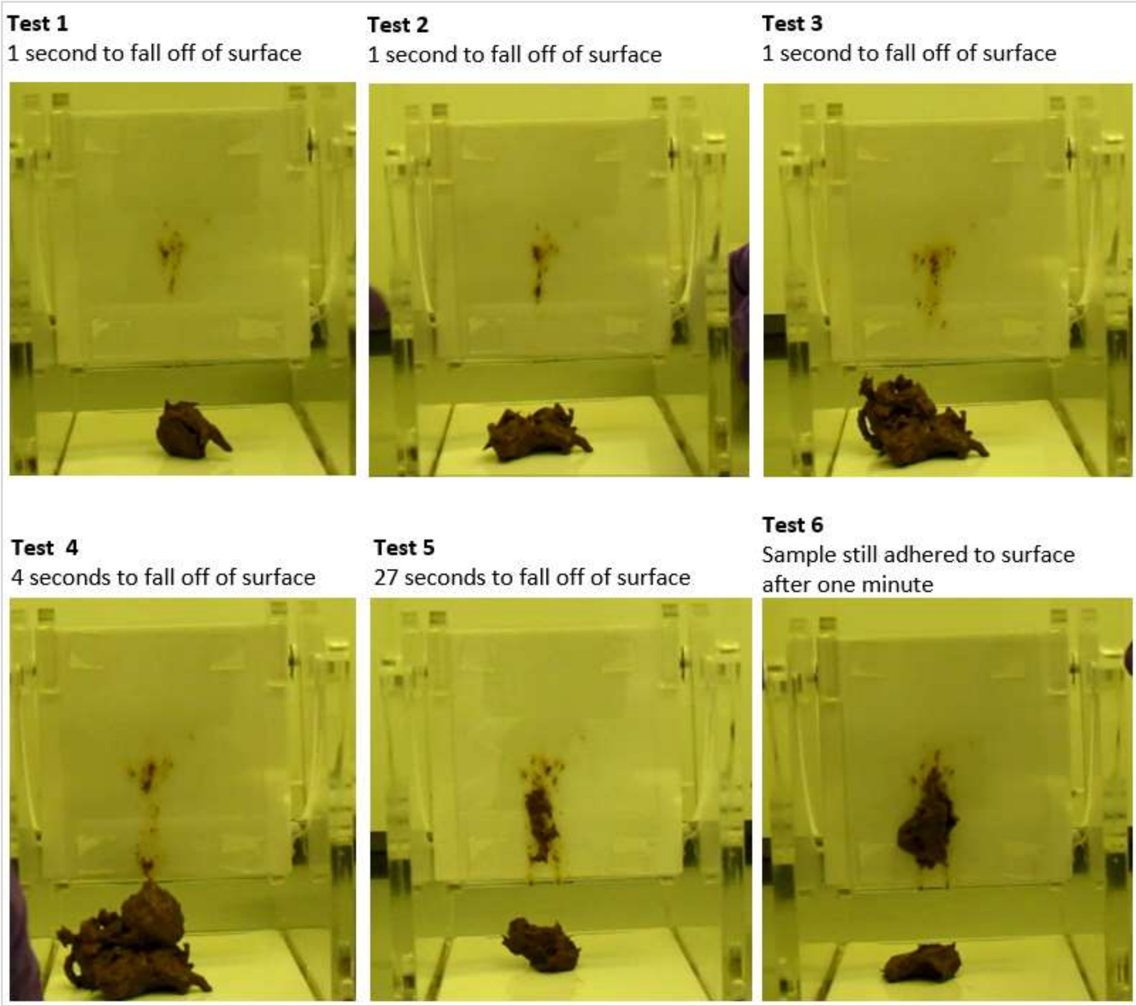


Figure 53 – Sequence of photographs taken after each dose of faeces is dropped on SLIPS with silicone oil. Testing the accumulation of surface fouling after repeated use and affect on repellency. (Tierney, R. 2017)

4.3.4 Material assessment

Table 12 provides an overview of the materials tested with faeces. As there are still a number of unknown factors with SLIPS, using traditional material comparison techniques such as an Ashby plot (Ashby and Johnson, 2013) or a Pugh decision matrix (Burge, 2011) is not appropriate. Instead, the advantages and disadvantages of each material tested are discussed in relation to practicality for waterless toilets.

Table 12 – Material comparison for toilets. Existing materials and SLIPS

Material and contact angle of material	**Advantages**	**Disadvantages**	**Summary**
ABS	- Low cost ($1.50-2.80 USD) [1] - Easy to process into desired shape[2] - Good scratch resistance[2] - Used in other low cost and low water toilets systems - High impact strength[2] - Ease of transport - High gloss finish[7]	- Likely fouling without water - High surface energy (38.5).	The best option for ultra-low cost sanitation options but will not provide a good user experience as fouling is likely due to a high surface energy
PTFE	- Widely used for toilets on trains and planes. - Excellent fouling repellency when used with vacuum flush and small volume of water. - Low-friction co-efficient 18.5mN/m[2,3] - High recycle potential[2] - High fracture toughness 5-7 Mpa.m[1]	- More expensive than other develop-plastics ($13.90-15.90 USD) [1] - Not ideal material for injection molding. - Repellency without water or vacuum needs to be measured. - If used as coating will need reapplying depending on use[4].	PTFE as a spray coating has the potential to improve repellency of waterless toilets whilst still being cost effective. Robustness and cost would need to be measured the benefit from fouling.
Ceramic	- Suitable for one-piece construction. - Low cost ($4-12 USD)[1] - Corrosion resistance. - Fine grain ceramic and enamel glaze ensures smooth surface finish[3] - Widely available material. - Fracture toughness 3.6-3.8 Mpa.m [1] - Glazed ceramic does not stain.	- Likely fouling without water. - More difficult to transport than thermos-plastic alternative due to weight and size	Ceramic is commonly used because the toilet can be cast from one piece that is able to support the weight of the user and can be easy to clean with water. It is also associated with the aspirational flushing toilet.
Silicone	- Low coefficient of friction 24mN/m [5]. - Suitable for batch run of production during testing[6]. - Anti-bacterial - Commonly used for sealing purposes[2]	- Flexibility will mean fixing to a support material or structure - Expensive ($7.20-17.20 USD)[1]	Material flexibility may help alleviate some concerns around tolerances within the flush mechanism but will have to be secured to a substrate or other structure for strength. Antibacterial and low surface energy could make it a practical material within sanitation.

Material and contact angle of material	Advantages	Disadvantages	Summary
SLIPS	- Excellent faecal repellency. - Simple reapplication of lubricant. - Low cost compared to other omniphobic surfaces[8]	- Only effective for a low number of tests. - Not currently widely manufactured - Cost likely to be considerably more than existing materials - Unknown environmental impact - Unknown long term performance - Unknown effect on rest of system - Consumable required	Faeces completely repelled for first few tests but began to foul as lubricant decreased. Improving robustness of lubricant could make SLIPS a viable material for use in sanitation. Concerns around other factors such as cost, manufacturability, environmental impact and maintenance must also be considered. Omniphobic materials in general could be hugely beneficial to the sanitation sector.

Table 13 – Material performance summary table

[1](Ashby and Johnson, 2013) [2](Lefteri, 2008) [3](Laughlin, 2011) [4](PSI, 2016) [5](3M, 2015) [6](Thompson, 2007) [7](Kulich et al., 2001) [8] (Glavan et al., 2013)

4.3.5 Summary of material assessment

ABS is well suited for ultra-low-cost sanitation options in developing countries but as the RWF is aiming to improve the user experience, a material with better repellency would be advised. PTFE is well used in waterless toilets in transport but did not perform well during testing in this stage. Antibacterial silicone could be very beneficial for sanitation and is recommended for further investigation. SLIPS with silicone oil performed exceptionally for the first few tests before lubricant depletion leads to surface fouling.

4.3.6 Summary of Stage Two and recommendations

A surface that can repel faeces and prevent fouling will improve user experience for a number of different toilets and could also reduce complexity of the Nano Membrane Toilet. If the excreta would freely to pass into a holding tank from the bowl during rotation without leaving any residue, the cleaning swipe blade would not be required simplifying the mechanism. The challenge is due to the varied consistency and content of faeces and a surface would have to display omniphobic properties to not be fouled. Omniphobic surfaces are a relatively new area of material science with trade-offs between performance, practicality and ease of production. Omniphobic surfaces such as SLIPS have great potential for this application but are still in their infancy. Development is needed to improve the longevity of SLIPS as reapplying silicone oil after every few uses would not be practical and could lead to other problems (for example; accumulated environmental impact of frequent use of lubricating oil). Fouling occurred on approximately the fourth test but other viscosities of the silicone oil should be tested further.

Recommendations for future work:

- Test application of non-stick spray coatings to the polyurethane bowl such as PTFE.
- Produce and test a rotating bowl with an antibacterial silicone surface such as in the CAD model Figure 54. Silicone not only has low-surface energy and is relatively easy to produce but can also be antibacterial. One method of designing this would be to print an internal core using SLS to ensure structure and form and then cast a silicone cover that would encase the outside of the print.
- Further investigation is needed to accurately assess SLIPS performance. Volume of lubricant required for surface area, repellency and longevity of different viscosities, environmental impact and practicality of application in different contexts would be key factors to fully establish.

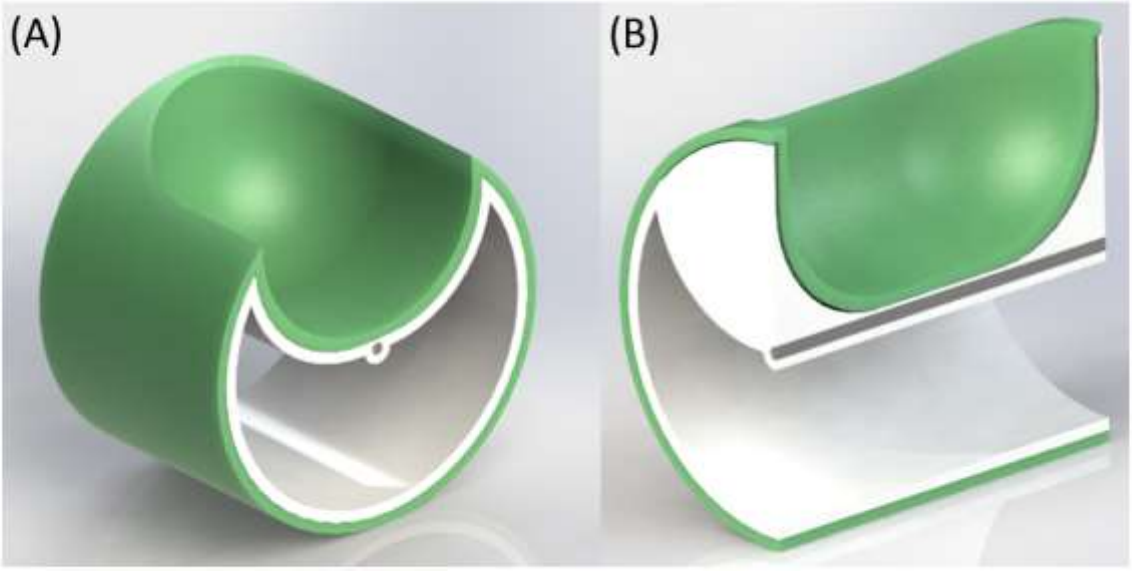


Figure 54 – CAD model of Silicone over-jacket concept (A) Cross section through bowl (B) Cross section across bowl (Tierney, R. 2017)

4.4 Stage 3: Cleaning swipe blade

To assess and reduce fouling of the rotating bowl to reduce risk of poor user experience.

A cleaning 'swipe blade' was proposed as a way to remove any remaining faecal fouling from the polyurethane bowl surface once the majority of the faeces had dropped into the holding tank by gravity. This stage set out to optimise the performance of the swipe blade to reduce the risk of surface fouling improving the user experience. The testing conducted by Koenen and Sanon (2007) investigating windscreen wiper performance was early inspiration for simplified testing of a swipe blade on a flat surface (Figure 55). This testing was later decided to be too dissimilar to the real rotating bowl due to a number of variables (e.g force on surface, speed of movement, and interaction on curved surface) and did not provide particularly valuable results to improve the rotating waterless flush.

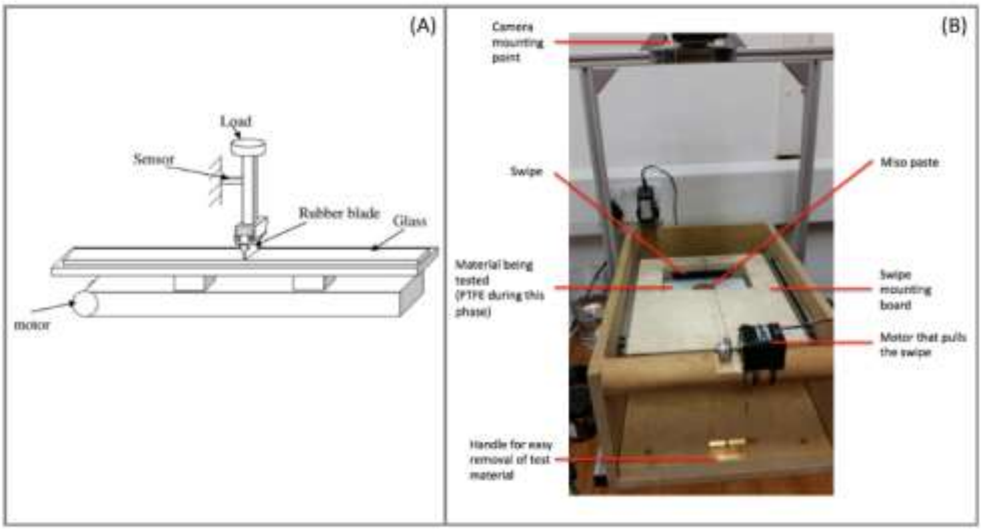


Figure 55 – (A) Testing apparatus used by Koenen and Sanon (2007) measuring contact of a windscreen wiper. (B) First swipe rig used for early testing. (Tierney, R. 2017)

Instead of the horizontal swipe test rig shown in Figure 55 (B), the user interface of P2 was used with a modular testing swipe blade (Figure 56). This blade was produced with FDM 3D printing and laser cut acrylic and assembled with standard M5 machine screws and M5 hex-nuts. The interchanging of blades tested different materials, sizes and shapes as well testing the interaction between different parts. Each swipe blade to be tested would be designed using the CAD software SolidWorks and laser cut from 3mm acrylic. This piece would be used as a template on the silicone and cut by hand. Every blade was inspected for cutting quality and any rough cuts or mistakes were rejected and remade to ensure reliability. Low-cost rubber was used for some preliminary test, before moving onto silicone that had already been identified as a potential material due to its flexibility and low surface energy. Silicone can also be engineered to be anti-bacterial with the addition of specific ions such as silver that would be advantageous in a toilet to help reduce malodour. Silver is widely used due to being one of the most powerful disinfectants known whilst also being low-toxicity (Jiang et al., 2004).

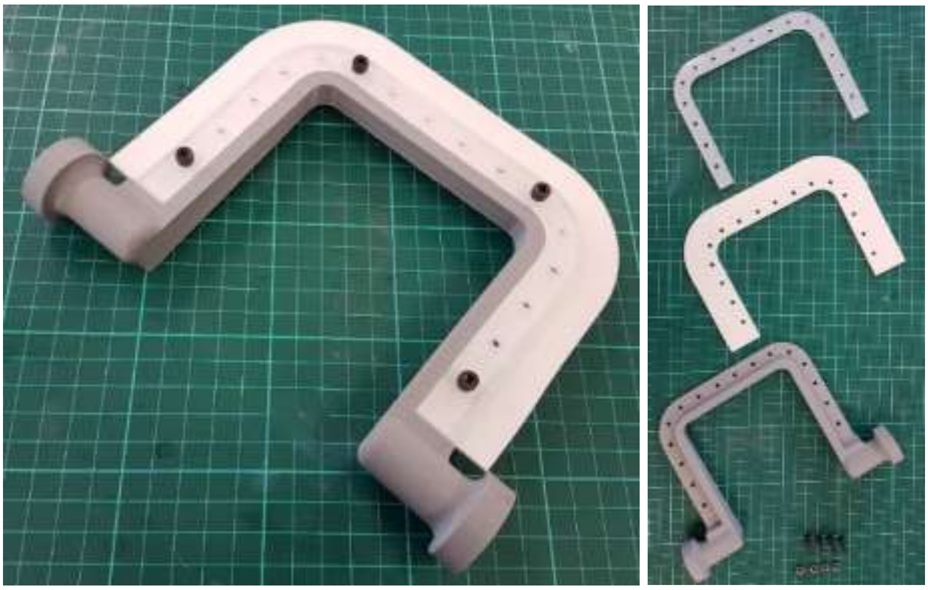


Figure 56 – Swipe blade with quick-change flexible insert (Tierney, R. 2017)

The preliminary swipe tests used 150g of soy bean paste in the form of three 50g cylinders dropped into the bowl similar to the MaP test (Gauley, 2016a) but the results were inconsistent and it was difficult to identify where the improvements to the swipe could be made. To improve the reliability of the tests a roughly even layer of soy bean paste was applied to the whole bowl surface by hand. This would make it easier to identify where the swipe blade could be enhanced.

Due to the complex geometry of the bowl, the shape of the cleaning swipe blade was tested and reshaped in increments, starting from the centre before including the corners then sides. The CAD model of the bowl was used as a basis for the shape with the first tests trying to get a clean channel from the front of the bowl to the back without leaving any soybean paste remaining as shown in Figure 57 (C).

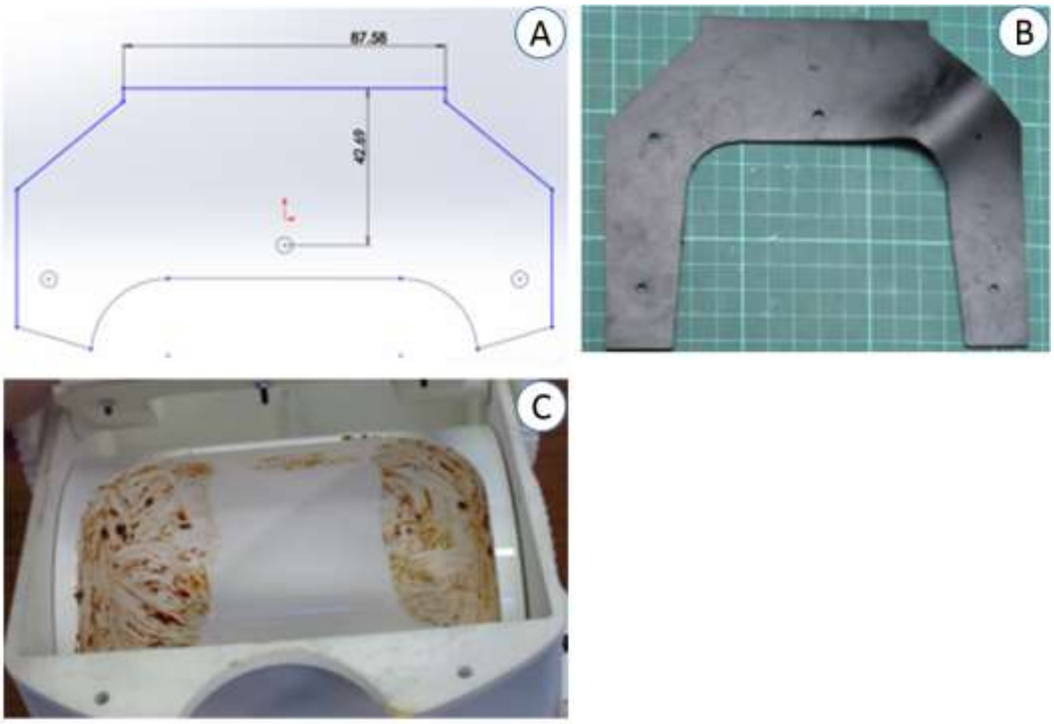


Figure 57 – A) CAD drawing of swipe blade 02. B) Swipe blade from 2mm rubber C) swipe performance. (Tierney, R. 2017)

Increasing blade length would apply more force on the surface and improve cleaning performance but would increase difficulty for the user. This would also affect how easily the blade can enter the bowl in the first place as it can get caught on the edge. 22 different swipe blades were produced and tested three times each with performance being recorded in the Table 14. Increasing width from the centre was an effective way to improve performance in small increments and be able to identify where problems arose especially when ensuring complete cleaning of the corners. Deformation occurred from too much pressure and leading to poor contact.

Table 14 – Swipe optimisation results

Swipe blade	Test	Feature of test	Observations
01	Rubber thickness. Without corners	Testing rubber as material.	Not strong enough
02	Rubber thickness.	Testing rubber as material.	Still too flexible
03	Rubber thickness.		Best performance
04	Silicone sheet	identify lower friction material blade	less friction same performance
05	Cleaning larger channel through centre of bowl	Blade length 39mm	not enough pressure
06	Cleaning larger channel through centre of bowl	Blade length 41mm	very good
07	Cleaning larger channel through centre of bowl	Blade length 43mm	difficult to move and missed section at beginning
08	Cleaning larger channel through centre of bowl	Blade length 42mm	straight clean line
09	Extending width of channel	5mm Extending in both directions	straight clean line
10	Extending width of channel	10mm Extending in both directions	deformation occurring
11	Extending width of channel	15mm Extending in both directions	deformation occurring
12	Cleaning corners of bowl	Corner shape A	deformation occurring
13	cleaning corners of bowl	Corner shape B	Centre of swipe raising
14	cleaning corners of bowl	Corner shape C	corners raising
15	cleaning corners of bowl	Corner shape D	deformation occurring
16	cleaning corners of bowl	Corner shape E	softer curve reduces deformation
17	cleaning corners of bowl	Corner shape F	uneven swipe
18	cleaning corners of bowl	Corner shape G	even clean
19	Cleaning sides	20mm	Small but noticeable force increase
20	Cleaning sides	30mm	reduced thickness to ease pressure works with no impact on cleaning
21	Cleaning sides	50mm	consistent clean
22	Cleaning sides	80mm	Virtually complete clean except small pieces on the rim

4.4.1 Summary of swipe blade optimisation

3mm thick silicone proved to be a suitable material for the swipe cleaning blade. Optimising the swipe blade required small incremental alterations due to the complex geometry and movement of swipe cleaning blade. The 22nd swipe cleaning blade shown in Figure 58, delivered a completely clean bowl surface.

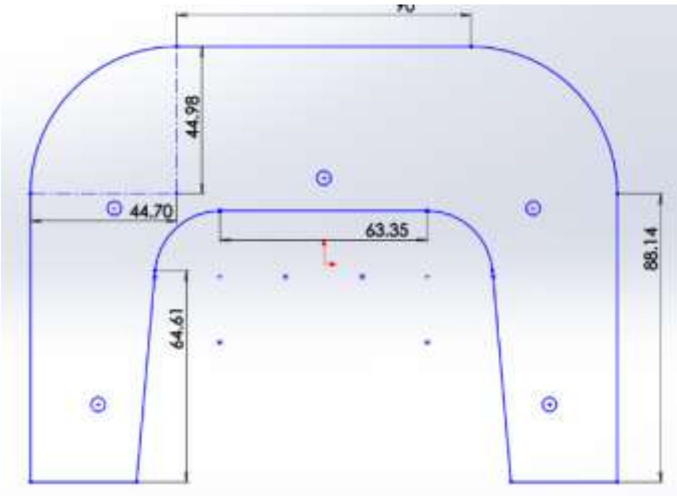


Figure 58 – Final swipe size and shape for swipe blade (Tierney, R. 2017)

4.4.2 Swipe hardness performance testing

The grading method for all elastomers such as silicone is shore hardness that is measured by a durometer which gives a shore hardness reading on being pressed into the material (Siddiqui et al., 2010). The silicone used during the swipe optimisation testing was Shore 60 and after 22 iterations of swipe blade it was providing a very high performance clean. To quantify performance, an image processing software, ImageJ, was used to calculate the surface area of the soy bean paste. This was done after application of the soybean paste and after the bowl had been swiped by the blade to measure the amount cleaned. Shore 80 was too hard to pass over the edge of the bowl and caused the driving belt to slip on multiple tests which was deemed to be a failure as it was unable to make it past midway on the pass through the bowl. Table 15 shows the results from testing ‘swipe blade 22’ made from shore 60 and the identical shaped replications in three different shore harnesses (shore hardness 30, 40 and 80). These blades were all water jet cut to ensure the most accurate shape, this method wasn’t appropriate during the earlier optimisation stage as it is time consuming and costly. The images from testing can be seen in Figure 59. Shore 30 performs half as well as Shore 60 but it would be interesting investigate the effect of material thickness and shore hardness. A thinner swipe blade of the harder material could perform better.

Table 15 – Shore hardness performance on cleaning of bowl fouling

Shore hardness	Area covered with simulant	Area of remaining simulant	Reduction of fouled surface
30	1073344	615221	42.68%
40	966966	202811	79.03%
60	969637	55449	94.28%
80	-	-	-

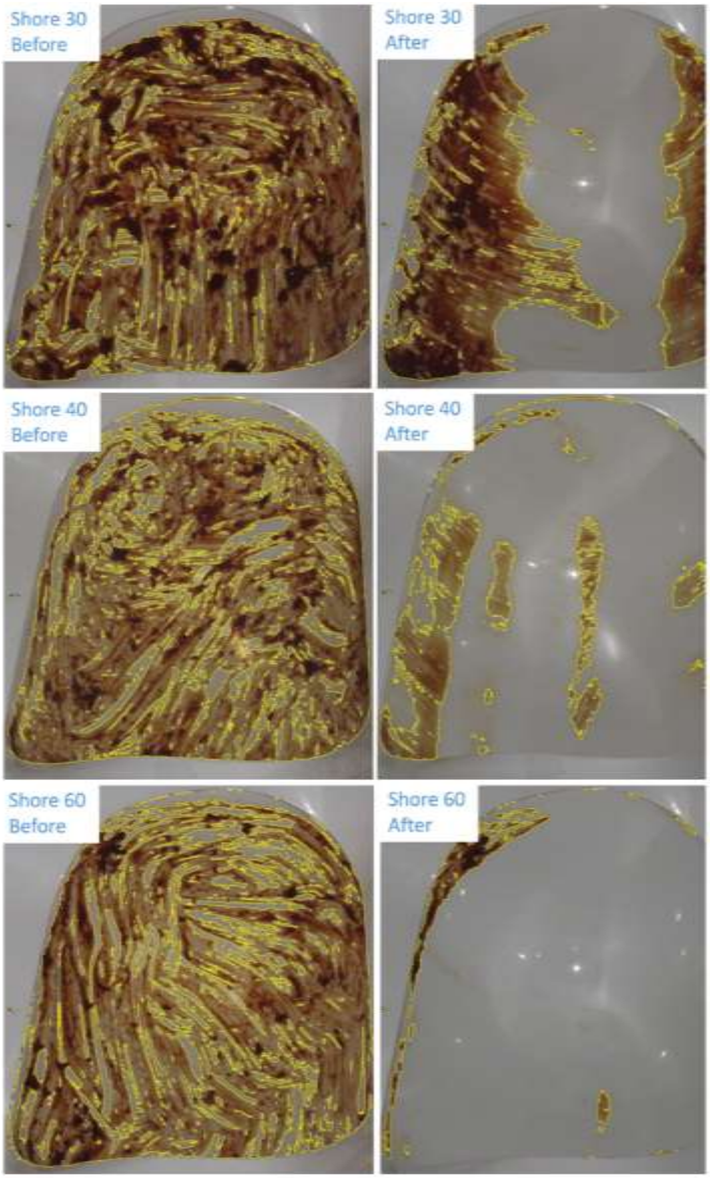


Figure 59 – Before and after images testing performance of different swipe blade shore hardness shown in Table 15. Yellow outline of fouling is used by ImageJ for measuring surfaces area. (Tierney, R. 2017)

4.4.3 Reducing swipe fouling

The function of the swipe blade is not to push faeces off of the bowl but more to lift the faeces from the surface of the bowl. Due to the rotation of the bowl, the faeces should drop below once free from adhesion to the surface. The shape of the outside edge is what determines a good clean, therefore a simple way to reduce the amount of faeces that can accumulate on the swipe blade is to reduce the surface area of the swipe blade (Figure 60).

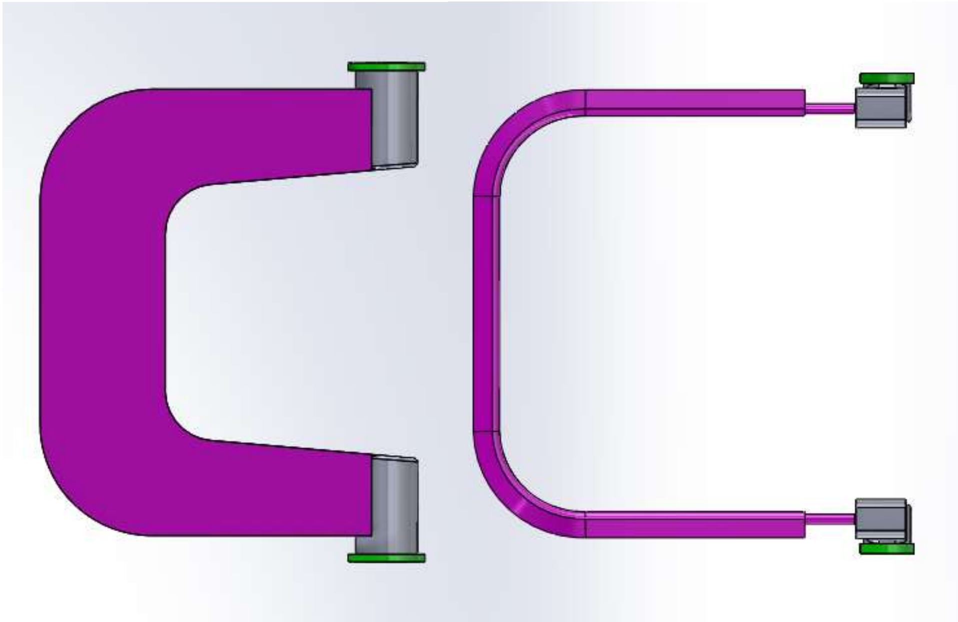


Figure 60 – Original swipe and reduced surface area bar swipe concept. (Tierney, R. 2017)

Instead of silicone sheet that had been used previously, the new bar concept would use silicone extruded through a specially designed die to give a 'teardrop' profile. A test of the teardrop concept used 3D printed rubber produced using FDM over a circular profile bar. This test was unsuccessful as the rubber shape would rotate and deform and a non-circular bar would be needed for this to work better Figure 61. It is also still possible to extrude the antibacterial silicone which will also improve the performance of the blade from the user's perspective by reducing odour.

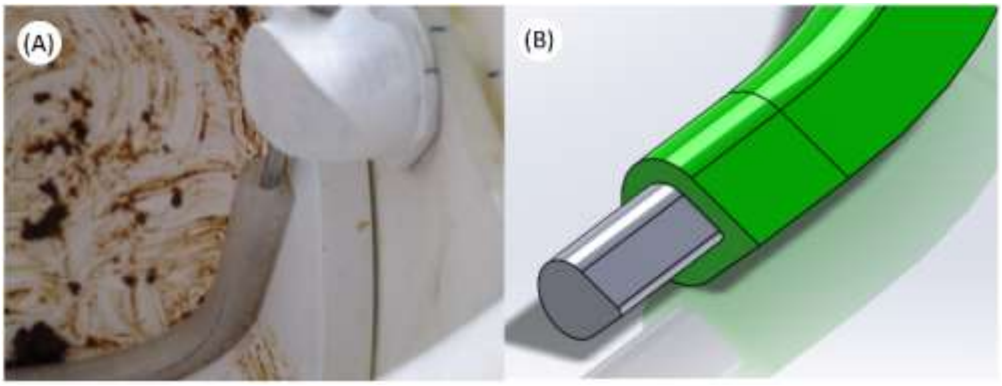


Figure 61 – (A) 'Teardrop' profile on round 4mm bar would roll and deform during a swipe testing. (B) To mitigate this, a teardrop profile bar with a flexible teardrop profile for the swipe material . (Tierney, R. 2017)

4.4.4 Repeated use testing

Once the swipe blade was optimised to effectively clean the whole bowl in one rotation, the performance of repeated use had to be tested. Faeces accumulating on the swipe blade was a concern raised by the design team during workshops and development of prototypes. To test for accumulation on the swipe blade, 150g of soybean paste (three 50g cylinders) was dropped into the bowl and then rotated multiple times (Figure 62). By closely observing each swipe of the bowl, it was noted that the bowl would be cleaned during rotation but soybean paste accumulated on the swipe blade would foul the surface when the swipe blade was returning to the starting position.

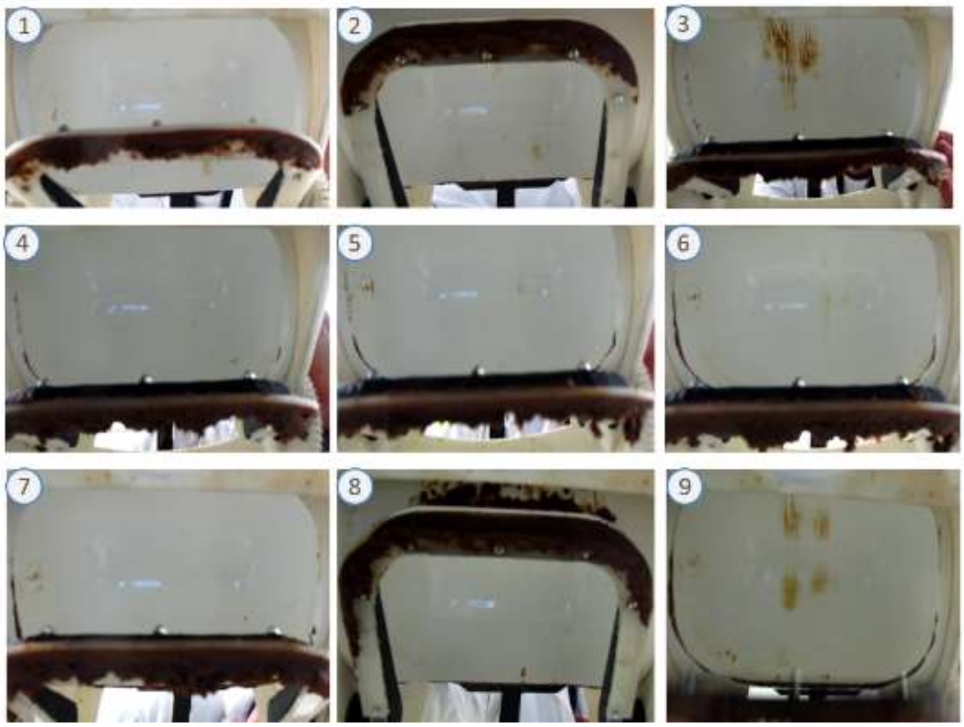


Figure 62 – Photos of inside of the rotating bowl during cumulative testing. (Tierney, R. 2017)

4.4.5 Addressing the effects of multiple use

A number of variables will affect how the RWF performs after multiple uses such as number of users, the ratio between defecation and urination and consistency of the faeces. To mitigate fouling caused by accumulated faeces on the swipe blade, a series of solutions were designed and most were tested. These ranged from simple methods to complicated mechanisms as shown in Figure 63. Parallel prototyping is a recognised method to encourage divergent explorations without becoming fixated on one design path (Martin and Hanington, 2012). The positive and negative aspects of each system was noted in Figure 64 to analyse each concept. The six approaches were:

A. Not conducting any additional cleaning of the swipe.
B. A passive method that required the swipe to continue its rotation and 'push' past a second cleaning blade. This provided very little improvement to cleaning during testing.

C. Spray jets of water were shown to be a viable method of clearing even severe swipe blade fouling by using 5ml syringes with nozzles reduced to 0.75mm. This focussed jet of water was enough to clear a 25mm diameter circle of soy bean paste from the swipe blade. To reduce the surface area of swipe blade the needed cleaned the thickness was reduced to 15mm. The system would still require 14 syringes to clean the whole swipe.
D. A linear secondary swipe performed well in tests but only along the final edge and could not clear the sides. It was also deemed too complicated due to requiring a timing delay mechanism.
E. The rotary secondary swipe blade wouldn't perform as well as the linear swipe and would still face the timing delay complexity and was therefore not prototyped.
F. The internally retracting swipe blade solved the problem of the fouled blade contacting the surface on the return and would also reduce force required to open the toilet. However it required a complex mechanism that would be at risk of failure from dried faeces.

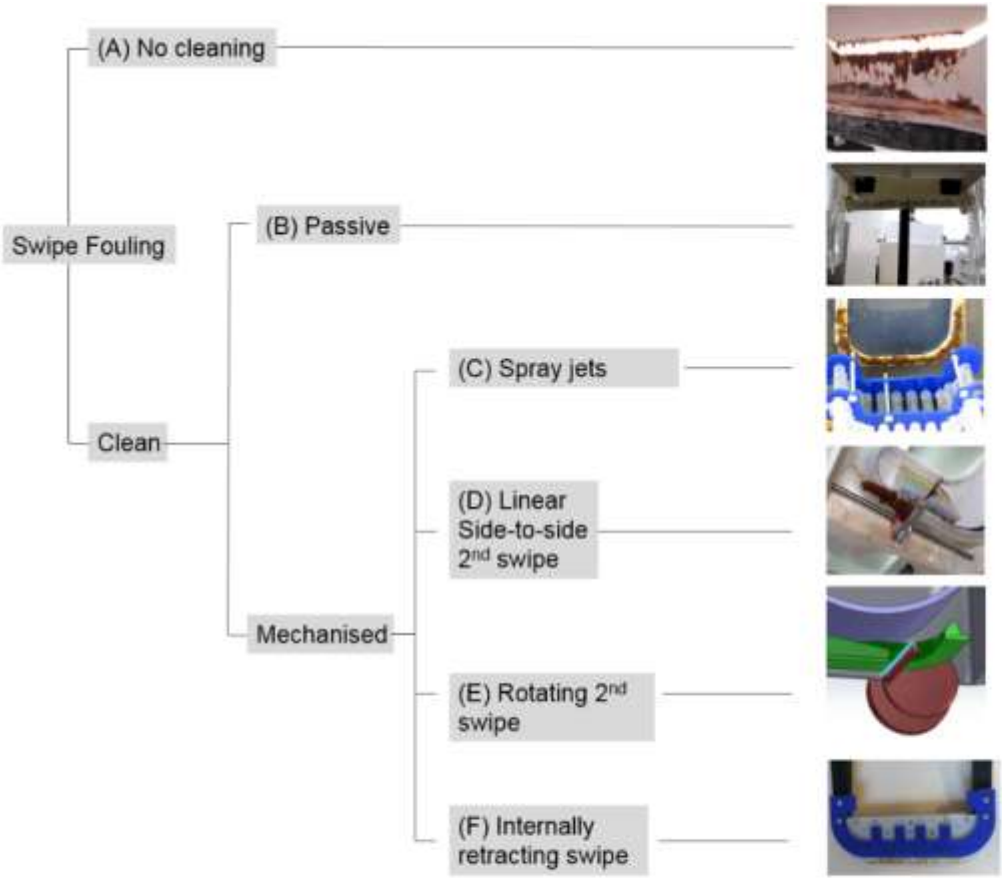


Figure 63 – Solution mapping the problem of swipe build-up (Tierney, R. 2017)

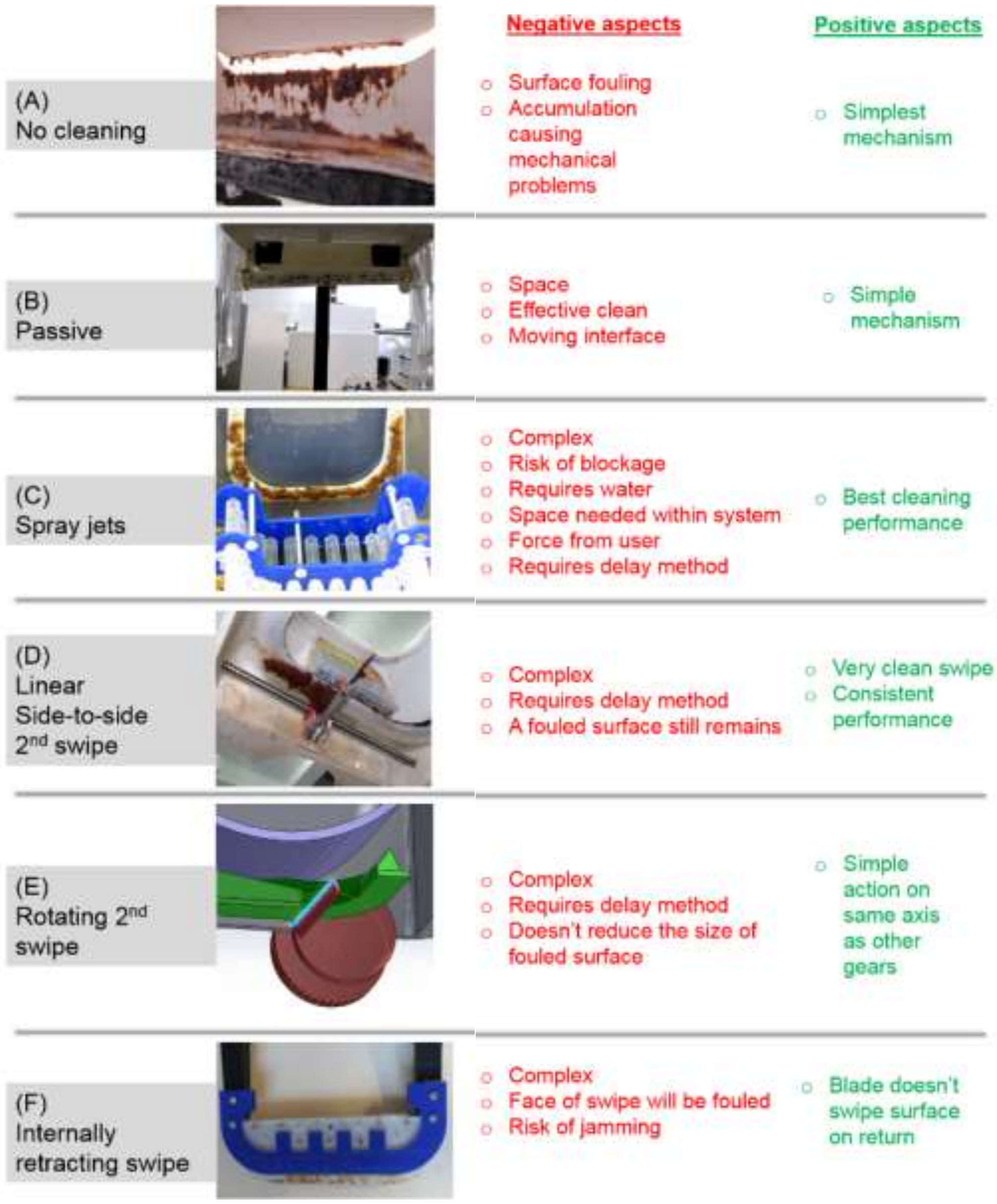


Figure 64 – Solution mapping positives and negatives of each concept(Tierney, R. 2017)

The solution maps in Figure 63 and Figure 64, along with prototypes and additional images were used during a workshop with the design team to discuss the viability of cleaning the swipe blade after each use. The spray jets of water cleared the soybean paste and were chosen by the design team as the best option for swipe blade cleaning (Figure 65) however they were deemed too complex to be included in the next prototype when the extent of the problem was not yet known. This stage gate meeting concluded that accumulation on the swipe may prove to be less of an issue as more urinations will occur than defecations which may help to reduce build up. It was therefore determined that until user testing identifies bowl fouling as a problem and subsequent investigation establishes that the fouling is caused by accumulation on the swipe, the added complexity was not essential and could cause additional problems to the basic function.

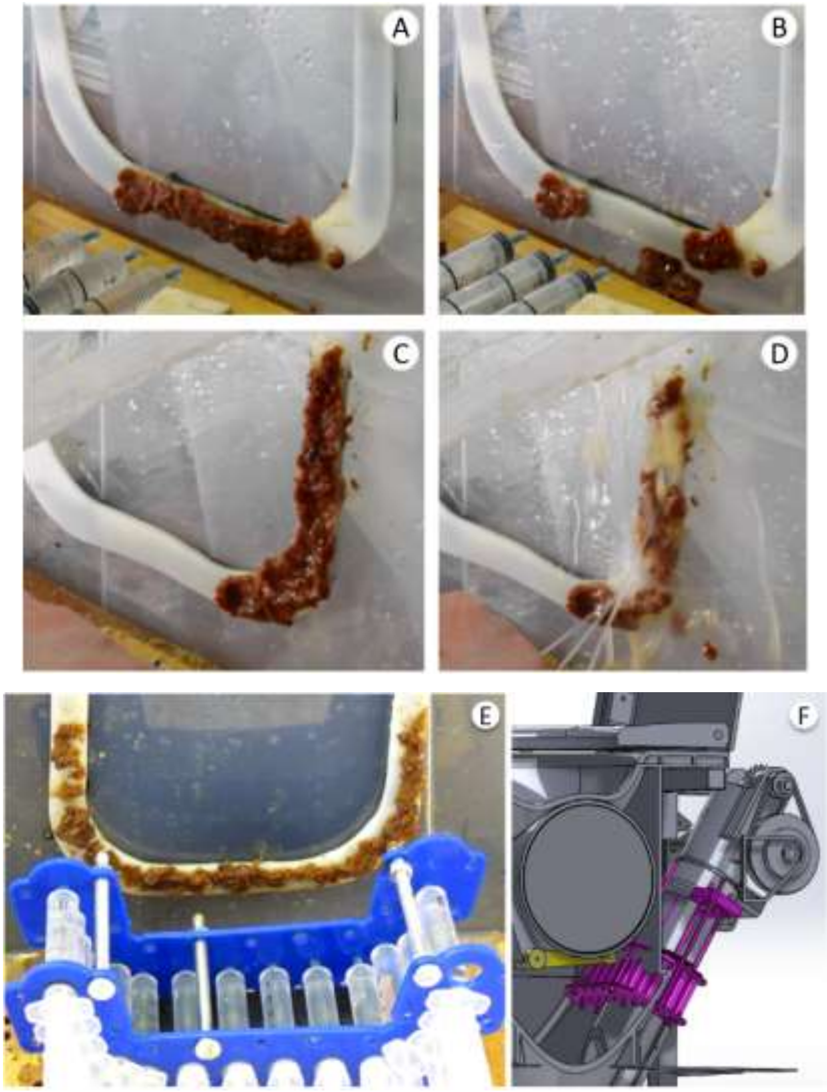


Figure 65 – (A) Soy bean paste loaded onto silicone swipe blade. (B) Silicone swipe blade after water spraying. (C) Soy Bean paste loaded during side testing. (D) Water jets spraying during side testing € Full spray prototype during testing (F) CAD model of spray system integrated into CAD model of full toilet system (Tierney, R. 2017).

4.4.6 Summary of Stage 3 and recommendations

The shape of the swipe blade was optimised to clean the whole bowl and shore 60 silicone was identified as the best material to use due to the low surface energy and antibacterial properties. A longer swipe blade causes more force on the bowl resulting in a better clean in sections with full contact, but it will not enter the bowl correctly and not provide a reliable clean. Fouling from multiple defecations was shown to be a cause for concern mainly caused from accumulated soybean paste on the swipe blade. Six cleaning methods were proposed to remove faeces off from the swipe blade after each use. The added complexity of the secondary cleaning methods were determined to be too much of a risk at such an early stage but will be considered at a later date if the problem is confirmed.

Recommendations

- Cast silicone swipe blade for testing in the next prototype (P3).
- Continue SLIPS development and testing.
- Develop and test a silicone blade with reduced width to decrease surface area for fouling.
- Assess accumulation of faeces from multiple swipe uses and if secondary cleaning method is required.

4.5 Chapter analysis

This chapter gave an insight into the iterative process and testing required to develop a new user interface for a waterless toilet. Figure 66 (at the end of the chapter) gives a visual overview of key developments of the chapter and the outcomes of each stage. The rotating flush technology profiled in this chapter was intended to improve the user experience of the Nano Membrane Toilet, however there is potentially further applications. This could be in the form of a subsidiary product that can be combined with other new sanitation systems or simply an add-on to improve the user experience of pit-latrines. Toilet collection services in urban environments such Clean Team in Kumasi, Ghana benefit from RWF. This would require a redesign the top section of the toilet to incorporate the RWF which would be compatible with their current toilet and service and will improve the user experience.

The transferability of the RWF is due to the core offering of; blocking user contact with stored excreta without any additional power, water or change to user behaviour. The stage gate process of this chapter ensured key deliverables were met during the development and testing of the technology using industry standard methods when necessary. The RWF was improved under lab conditions using simulant faeces and real faeces. Testing with real faeces is essential during development of new sanitation technology but raises a number of challenges and not just unpleasantness for the tester. Collection, storage and disposal of samples has to be carefully planned as does appropriate health and safety measures during testing. Soy bean paste was found to be the best material for simulant testing due to its ready availability, low cost and similar appearance and consistency. More information on testing with real feaces and simulant faeces in in Appendix A.3.

Areas for further investigation were stated at the end of each stage. The use of omniphobic surfaces within sanitation is one of the key areas that offers great potential for the sanitation industry but requires more research and development. As these materials are relatively new, their use within sanitation had not previously been linked before this research. These tests have been used in one publication currently being peer reviewed at Nature Communications. The silicone swipe blade will be incorporated into the next prototype (P3) that is currently under construction. A silicone bowl and reduced width swipe blade were also proposed for further development to improve the performance further. Faecal fouling is a frustration and cause of negative user experience to all toilet users and preventing this is challenging due to the nature of faeces. The RWF will require further development and has been developed to the point that it is ready for real user testing. The component has been protected with a granted international patent WO2017149036 (appendix A.8) with the author listed as an inventor.

4.6 Chapter Four highlights:

This chapter presented the development and testing of the RWF charting key stages from low level cardboard models to a complete prototype ready for user testing. Developing technology for toilets raise a number of alternative challenges to the innovation path. Preventing faecal fouling will improve user experience but is very difficult is very difficult due to the viscoelastic nature and varied consistency. Repelling faeces without water could not only improve waterless toilets in developing countries but any scenario that could benefit from waterless toilets. One example would be on aeroplanes, although they already use a micro flush, any improvement to the surface could reduce the amount of water needed per flush. Reducing the water volume needed to be taken on board will reduce weight and therefore the fuel consumption and cost. Omniphobic surfaces have great potential for this sector by improving user experience without water but they are still in their infancy. SLIPS repelled faeces for first few tests but once lubricant diminishes, the substrate will be compromised and fouling will accumulate. Silicone has potential benefits to sanitation due to the flexibility, low-surface energy and antibacterial properties and has been recommended for more utilisation within the NMT. The following chapter will test the RWF with real people to establish performance of a waterless user interface and the potential for the technology to be adopted by a secondary target market.

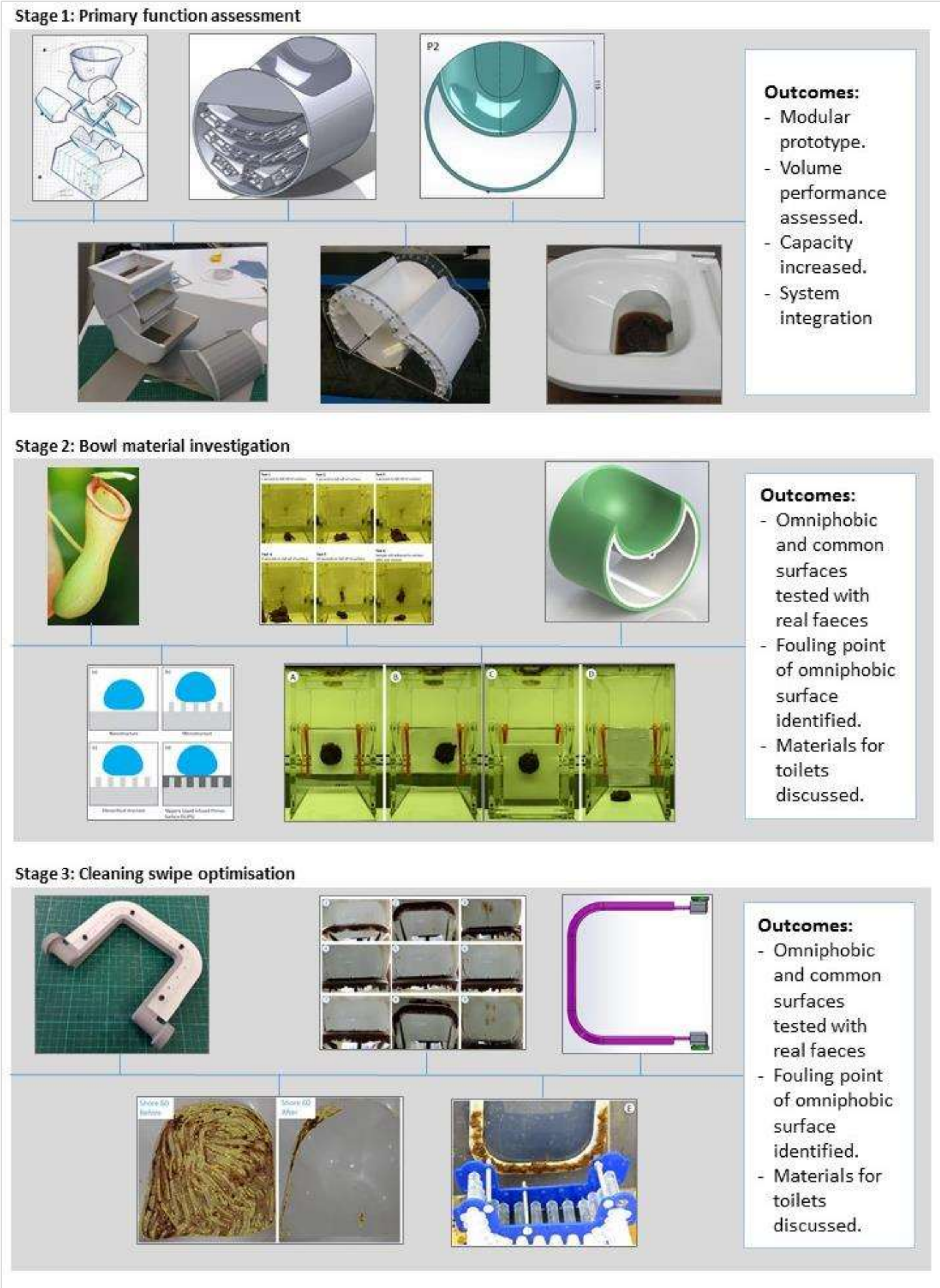


Figure 66 - Visual chapter overview (Tierney, R. 2017)

“The understanding of social issues is paramount if one intends to introduce an alternative sanitation system”

W.S. Warner, 1998

5 USER TESTING OF A WATERLESS TOILET TECHNOLOGY

Objective Four: *To evaluate the new technology with real users and the potential for waterless sanitation technology to be adopted in a secondary target market.*

This chapter will discuss the testing of the Nano Membrane Toilet (NMT) user interface and the potential of the RWF technology to transfer to a secondary target market. Figure 67 illustrates the three sections of the chapter with the associated test and rationale below each part. The structure will evaluate performance, inform future prototypes and assess the transferability of the RWF. As the RWF was designed for a primary target market in a developing country, investigating transferability of the technology to a developed country would provide better understanding of the potential for reverse innovation with this product. Key findings will be presented at the end of each of the three sections. Concluding the chapter will be a chapter analysis drawing together the key findings, future work recommendations and limitations of research.

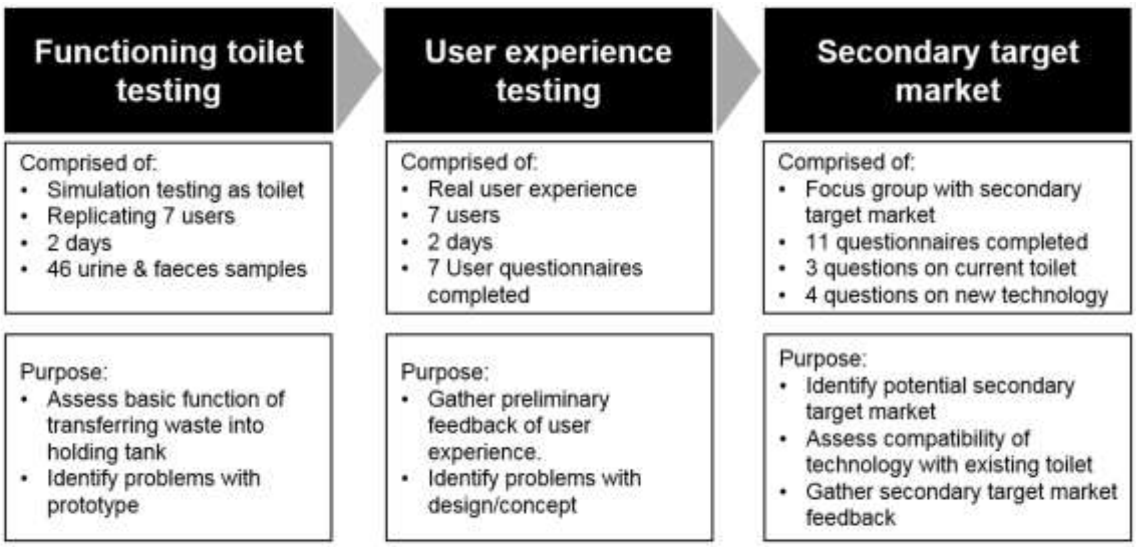


Figure 67 – Diagram of chapter structure with tests and rationale

5.1 Functioning toilet test

The purpose of this test was to establish whether the toilet prototype could perform the basic function of the RWF and to identify any issues that arise during use. The function of the RWF is to transfer excreta away from the user into the holding tank below, driven by the action of closing the lid after use. The test simulated the toilet being used by seven people for two days, using real faeces and urine stored in sealed containers. The samples of real excreta had been donated by volunteers in a designated donating toilet area prior to testing. Additional information on excreta sample procedure can be found in Appendix health and safety and ethical considerations can be found in Appendix D. The testing method involved recording the quantity of an excreta sample before emptying the container into the rotating toilet bowl and closing the lid to drive the rotating action. This was repeated for all 46 samples, however due to lack of urine samples, water was used from test number 22 test onward. All key observations were also recorded, monitoring prototype performance with a focus on the pan and rotating bowl. Examples of issues and key observations that the team foresaw was gear misalignment, surface fouling and leaks from the holding tank. The testing took place in a disabled toilet room (shown in Figure 68) that provided suitable space for the testers and equipment as well as being a 'wet room' to allow for appropriate cleaning after testing. Toilet paper was not included in the test as the Nano Membrane Toilet system would not be able to process paper and is therefore strongly discouraged from disposal within the toilet. In the target market of Kumasi, Ghana a paper bin next to the toilet was seen on a number of occasions, even in public toilets and was therefore not considered as requiring any change to normal user behaviour. More information on the cleansing practices from Ghana can be found in Objective Two.

Figure 68 – Photograph of toilet prototype in position in testing room before testing with author and lead investigator for tank settling (Tierney, R. 2017)

Simulating user activity user activity as closely as possible was important in order to gain the maximum insight from the testing. Real faeces was dropped into the bowl and urine was poured onto the front of the pan. The excreta was stored in the holding tank over night to identify such issues as leaks from an extended period of use. The testing focused on the toilet pan and bowl (Figure 69) but complete prototype performance was also assessed. A simultaneous experiment was taking place to observe the settling of faeces at the bottom of the holding tank as this was a crucial factor for how the NMT will process the excreta.

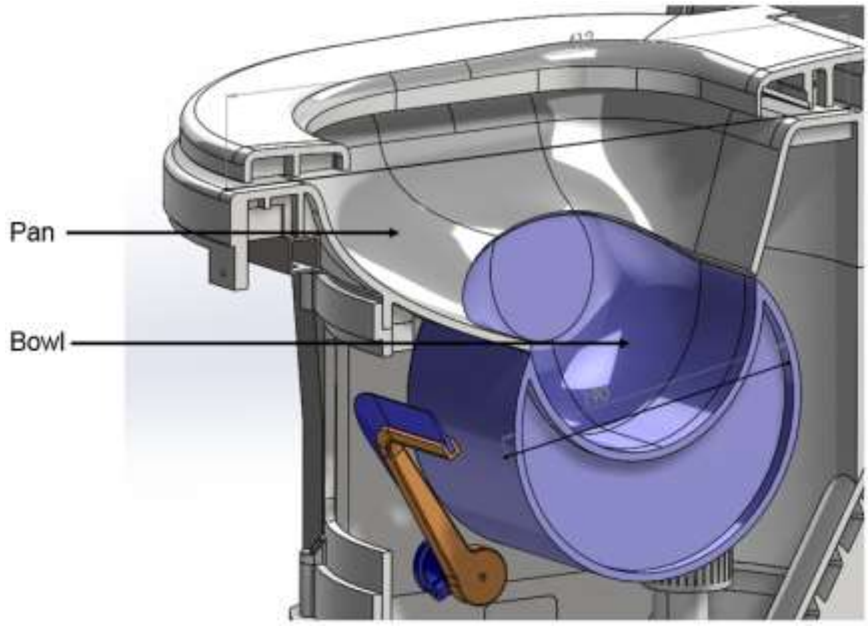


Figure 69 - Cross section from CAD model of toilet showing pan and bowl. (Tierney, R. 2017)

Table 16 displays the excreta quantities and corresponding observations from the testing. An 'event' refers to each time samples were emptied into the rotating bowl and the lid was closed. Only key events are displayed in Table 16, all events that were not shown in this table were only urine between 200ml and 400ml informed by (Rose et al., 2015b). When no observation was made the abbreviation 'n/o' was used.

Table 16 - The key observations from the user interface tests that simulated approximately seven people using the toilet for 24 hours with real faeces

Event	Liquid (ml)	Faeces mass (g)	Pan observations	Bowl observations
1	230	0	Urine pooling on ridge of pan (pre flush) splattering on surface. Pooling disappears with flush. Still urine present.	Still urine in bowl after flush. Underside of bowl appeared wet. Smearing?
2	300	0	n/o	Still urine after flush
5	330	128	Fouling on pan even after urine	Light smearing after swipe. Only on left side

Event	Liquid (ml)	Faeces mass (g)	Pan observations	Bowl observations
6	400		Urine cleared some fouling off	Urine cleaned some faecal smudging
7	400	0	n/o	Some self-cleaning occurred
9	400	0	n/o	Bowl almost completely cleaned
10	400	130	Faeces left around rim. Urine/faeces still in bowl after flush	Lip of pan & bowl catching - causing smudge on underside of bowl
11	400	0	cleans faeces smearing on front (not on back)	Still fouling on back and underside
12	400	0	n/o	Faeces on back of pan/bowl dropped into bowl with liquid
13	400	0	n/o	Stayed in bowl
14	400	0	n/o	Flushed down
16	200	205.17	Urine drops	Severe fouling, huge swipe marks after flush
17	200	258.84	n/o	Huge swipe marks after flush
19	400	0	n/o	Starting to clear faecal residue
21	400	0	n/o	Front of bowl less fouled than back
25	200	153.17	n/o	Sharp swipe line in bowl
33	400	0	n/o	Lip from bowl seems further away from pan
35	400	0	n/o	Brown liquid on bowl, maybe from swipe coming in contact with liquid in holding tank and fouling clean bowl on return to open position
37	400	0	n/o	Odour released as bowl rotates to the open position (aka stink bomb)
46	400	0	urine residue	No faeces, brown liquid visible

5.1.1 Summary of pan observations

The following observations are a summary of pan performance from the testing that simulated normal use with real excreta. Urine pooling on the rim of the pan as shown in Figure 70 - Photograph showing urine pooling on edge of pan, occurred after every test and is a design issue to be addressed with the next prototype. This is a problem as the urine would accumulate and begin to smell and all excreta should be in the holding tank. Urine droplets on the surface of the pan were also observed but this was due to the pan material rather than pan geometry. A pan material with a lower surface energy than polyurethane could help to alleviate this. Faeces that landed on the pan rather than in the bowl will only be cleaned if urine removed it. Faeces getting caught between the rotating bowl and the pan was identified as a potential problem and that future pan designs will have to address.

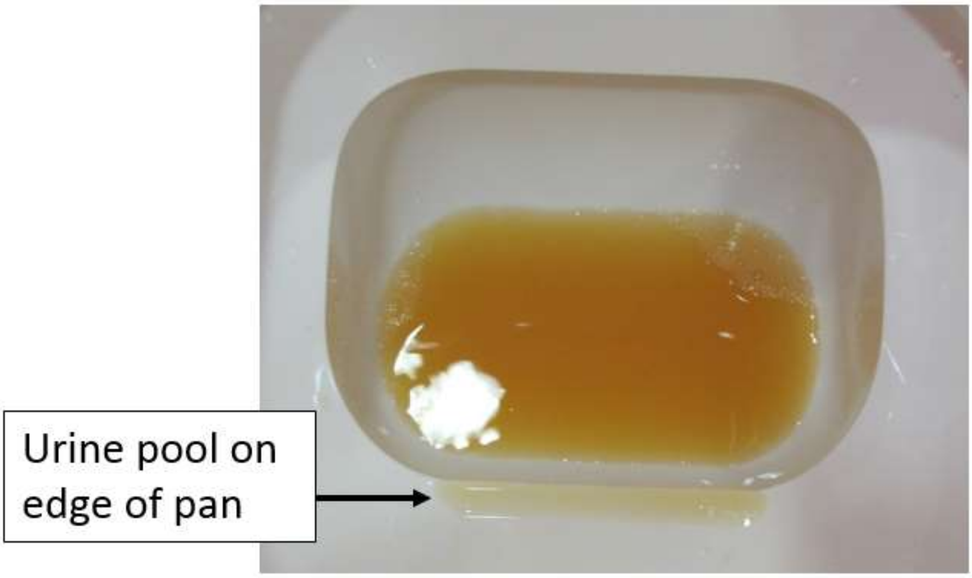


Figure 70 - Photograph showing urine pooling on edge of pan (Tierney, R. 2017)

5.1.2 Summary of bowl observations

The following observations summarise the bowl observations made whist simulating intended use with real excreta. The tests where faeces were introduced into the bowl before liquid were very concerning as major fouling occurred as shown in Figure 71(A).The tests that introduced the liquid into the bowl before the faeces were very successful with very little or no fouling at all (Figure 71B). Fouling like this will likely cause major disgust for the user and will be unacceptable as a user interface. Another consideration is that unlike conventional toilets, the user won't be able to see if there is any fouling unless they open the lid again. The assumption could be made that once they've closed the lid, the bowl is clean. The order that faeces and urine will enter the bowl will vary and therefore urine cannot be relied upon to reduce the risk of fouling. The volume of the bowl was agreed by the team to be a good size as every sample could fit well within the confines of the bowl.

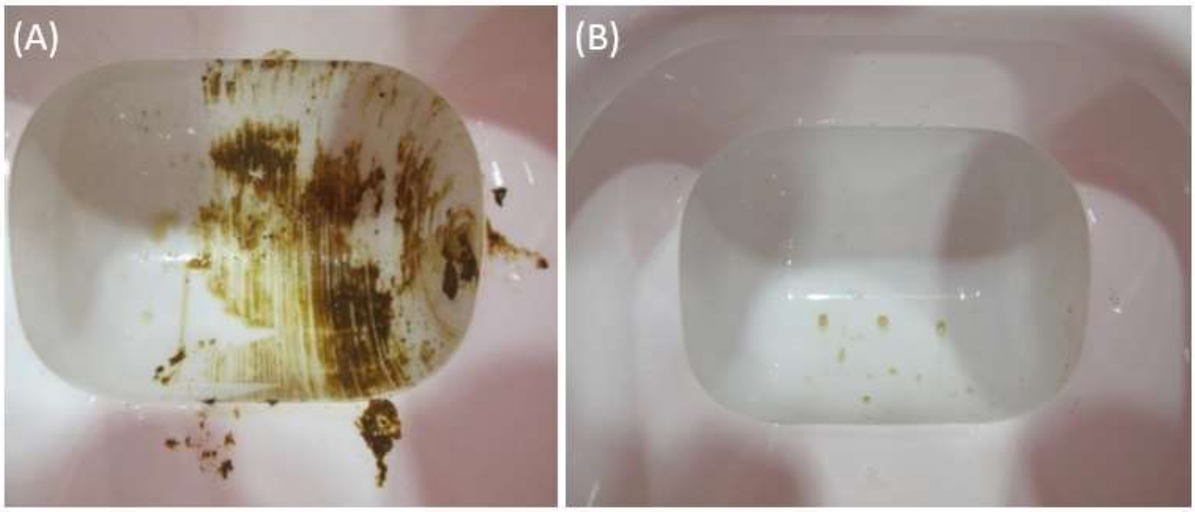


Figure 71 - (A) Example of severe surface fouling occurring from faeces (Bristol Stool Scale six) introdued before liquid (event 16). (B) photograph of toilet bowl with surface fouling cleared by multiple rotations and liquid. Brown liquid droplets visible. (Tierney, R. 2017)

5.1.3 Prototype observations

The toilet completed all 46 events with no mechanical failures or concerns. Each time the lid was opened and closed, a smooth motion was noted by both testers and there was no indication of jarring or misaligned gears which was a concern before testing commenced. As shown in Figure 72, a small amount of liquid was observed under the prototype on the second morning of testing which was a concern. After some investigation the leak was identified as coming from the observation port that allowed the settling test to take place. The clear acrylic port was secured with machine screws and a fitted rubber seal but a small amount liquid had seeped out. The next prototype will not need to facilitate this test and will therefore not need an observation port mitigating the risk of leaking from that area.

Figure 72 - Photograph of toilet prototype and enlarged area under prototype where liquid leaked from the holding tank overnight due to loose seal on the viewing port. (Tierney, R. 2017)

The room where the testing took place did not smell on the morning of the second day of testing. This indicated the odour seal of the rotating bowl had worked well. There was a strong odour when the lid was opened, which was a result of faeces building up in the holding tank. This odour build up then release was coined the 'stink bomb' by the testing team and would be a concern and an issue to address in future prototypes.

5.2 User experience testing

User feedback is a key component of product development and encouraged from the earliest point during the innovation path to improve the design of a product (Ulrich and Eppinger, 2000). Due to the sensitive nature of developing toilets, user experience testing can be less easy than other more conventional household products. Privacy and ethical consideration are all factors. The user testing was approved by Cranfield University Health Research Ethics Committee (CUHREC) that can be viewed in Appendix #. The user experience took place in the same large toilet that the simulation testing was conducted.

5.2.1 Results from user testing

The user feedback from the test is presented in the following three parts Figure 73, Table 17 and Table 18. Questions using the Likert scale give quantifiable results to the user interaction whereas open questions will give more detail and insight to the human interaction testing (Brace, 2008). To begin with, the compiled results from the three Likert scale questions are presented in Figure 73. The number of respondents who selected each answer is in the box below each option. An overall positive impression can be gathered from these responses with only one answer from the 21 responses being below average and five responses being the highest.

Q1 - How would you describe your first impressions of the toilet?

	Very good	Good	Average	Bad	Very bad	Total	Weighted Average
Response	42.86% 3	42.86% 3	14.29% 1	0.00% 0	0.00% 0	7	1.00

Q2 - How easy was the toilet to use?

–	Very easy	Easy	OK	Not easy	Difficult	Total	Weighted Average
Response	14.29% 1	71.43% 5	0.00% 0	14.29% 1	0.00% 0	7	2.14

Q3 - How did you find the experience of using the toilet?

	Very comfortable	Comfortable	Fine	Uncomfortable	Very uncomfortable	Total	Weighted Average
Response	14.29% 1	42.86% 3	42.86% 3	0.00% 0	0.00% 0	7	2.29

Figure 73 - Results from questions 1-3

The additional comments from questions one, two and three are shown alongside which respondent expressed the remark (Table 17). Not every respondent chose to give further detail on the Likert scale and these are identified with 'no comment'. The questions are arranged across the top of the table with each respondent and their gender listed below.

Table 17 – Additional comments to questions 1-3

Campus Respondent	**Q1) How would you describe your first impressions of the toilet?**	**Q2) How easy was the toilet to use?**	**Q3) How did you find your first experience of using the toilet?**
1 Male	*No comment*	*No comment*	*No comment*
2 Female	"The non-rotating section of the bowl was dirty from previous users"	"The lid was quite hard to open"	"Does the step need to be longer? It felt a bit like I was at risk of toppling off!"
3 Male	*No comment*	*No comment*	"The step didn't protrude far enough for my legs - my knees were slightly bent so my feet could rest on the step rather than overhanging it".
4 Male	"It looks a lot like a standard toilet –	"The lid is quite hard to lift"	"The water tank makes getting on to the toilet a bit odd. I was

Campus Respondent	Q1) How would you describe your first impressions of the toilet?	Q2) How easy was the toilet to use?	Q3) How did you find your first experience of using the toilet?
	that's a good thing in my opinion"		surprised that the odour was quite low. There was smearing on the bowl but not bad and it looks like it could be easily cleaned. Not wishing to get too anatomical but there is not much room for one's gentleman's parts at the front of the bowl when sitting".
5 Male	"Very clean looking – good first impression"	"Lid was stiff to lift – perhaps difficult for a young or elderly person to lift"	*No comment*
6 Female	*No comment*	*No comment*	*No comment*
7 Male	*No comment*	*No comment*	*No comment*

Table 18, presents the replies to the open questions (four, five and six) and which respondent made the comment.

Table 18 - Responses to open questions 4-6

Campus Respondent	Question 4: What aspects do you like about this toilet?	Question 5: What aspects do you dislike about the toilet?	Question 6: How did your experience compare to your normal toilet?
1 Male	"The bowl was clear and it was aesthetically pleasing on the eye"	"The smell was intense because someone had just used it. Despite the fact that the bowl was very clear and nice, the edge around it was dirty (covered with urine and hair)."	"I would say similar experience apart from the smell in the room and the dirty bits around the bowl that made me consider it twice before I take a seat."
2 Female	"Not using any water to flush!"	"It looked like some of my urine was left behind on the lip of the bowl"	"Comparable"
3 Male	"Was easy to use and felt comfortable - no splashing! And no splashing noises..."	*No comment*	"Different to not put toilet paper inside".

Campus Respondent	Question 4: What aspects do you like about this toilet?	Question 5: What aspects do you dislike about the toilet?	Question 6: How did your experience compare to your normal toilet?
4 Male	"That it is so similar to a standard toilet"	"The water tank at the front and the stiff lid. I would like to put toilet paper into it too"	"Different but not hugely so. Need to use it lots of times. When using for the first time one thinks about it more than one would normally."
5 Male	"Not pumped into a system"	"Slight odour in the room"	"It was unusual to not have a flush handle."
6 Female	"Looks great, novel flush"	"Slight odour when opening lid"	"Intuitive and fun experience".
7 Male	"Very clean white bowl"	"Urine droplets visible on pan from previous use."	"Very similar. Overall a good experience".

5.2.2 Findings of user experience testing

A positive user experience was captured from the survey responses. Six of the survey questions aimed to assess user perceptions and experiences, prompting positive and negative reactions. First impressions were encouraging, with responders being impressed by the overall appearance baring similarity to a conventional flushing toilet even though there is no water (Campus Respondent 04 "It looks a lot like a standard toilet – that's a good thing in my opinion"). The RWF being driven by closing of the lid was noted as being 'novel' and 'intuitive' (Campus Respondent 06) as well as two others noting to the clean white appearance being attractive (Campus respondent 07). The only mention of splashing was explaining satisfaction that "…no splashing! And no splashing noises" which was a concern prior to testing (Campus respondent 03). Negative comments mainly referred to fouling and "…dirty bits" on the part of the bowl that doesn't rotate, as well as malodour (Campus respondent 01). 'Ease of use' was the only question that was answered with a below average response and all three comments relating to this question mentioned the lid being difficult to open ("The lid was quite hard to open" Campus Respondent 01). Whether this is just because closing the lid requires noticeably more force than a conventional toilet or the act is genuinely difficult will require further investigation.

5.3 Secondary target market

The primary target market of the RWF was Kumasi, Ghana as the community have poor sanitation access. The secondary target market would be an alternative community in a developed country who use waterless toilets and will face many of the same challenges as the people in Kumasi. Although everyone needs a toilet, it is unlikely that a typical western flushing toilet user would trade their toilet unless the same convenience and cleanliness can be obtained (Black and Fawcett, 2008). An 'eco-community' were identified as being the best option for a secondary target market as they are also 'lead users' of waterless toilets[20]. Von Hippel (1986) promotes the benefit of using lead users when developing new products as they can help to "expose user needs not obvious from observing a standard user". An eco-community could also benefit from an improved design waterless toilet which is another of Von hippel's characteristics for identifying Lead Users (Goffin, Lemke and Koners, 2010; von Hippel, 1986; Judge, Hölttä-Otto and Winter, 2015).

5.3.1 Compatibility with secondary target market

Eco-communities are off-grid that often practice a self-sustaining lifestyle and promote recycling of resources. Eco-sanitation allows people to convert their excreta into compost, a valuable fertilising material used in improving crop growth (Kvarnström, 2006). Good composting procedure states that urine should be kept separate from the faeces to ensure an effective ecological process (Anand and Apul, 2014). It was not feasible to produce a new urine diverting pan for the demonstration and testing. To mitigate this, Composting toilets tend to promote the addition of sawdust. A series of laboratory based tests were conducted to

---

[20] Other markets considered were camp sites, festivals, military stations and construction sites but the eco-community are the only everyday users of a waterless toilet and also advocate their use over flushing toilets.

ensure the RWF would be compatible with such a practice. These tests used soybean paste to simulate faeces. Figure 74 shows before (A) and after (B) one of these tests was completed. There was no fouling from the soybean paste and no sawdust remaining in the rotating bowl.

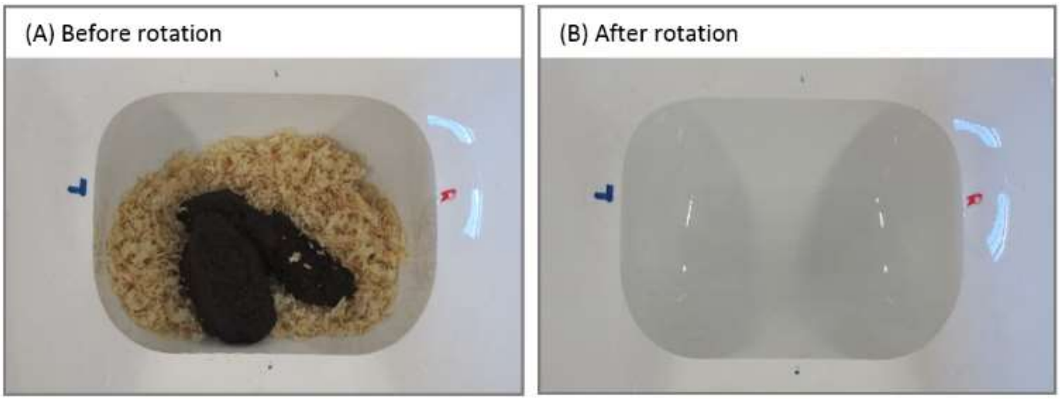


Figure 74 – Photo before (A) and after (B) Lab testing the RWF using 150g soybean paste dropped onto sawdust (Tierney, R. 2017)

Adding sawdust to the bowl before use acts as a sacrificial layer, similar to how the lubricant performs on the omniphobic material; Slipper Liquid Infused Porous Surface[21] (SLIPS) (Wong et al., 2011). The layer of sawdust prevented soybean paste from coming in contact with the rotating bowl surface so there was no fouling as explained in Figure 75. As there was no fouling, tests with the swipe blade removed were performed with the same positive results with less force required to close the lid.

[21] More information on Omniphobic surfaces and this material in particular, can be found in Objective 3.

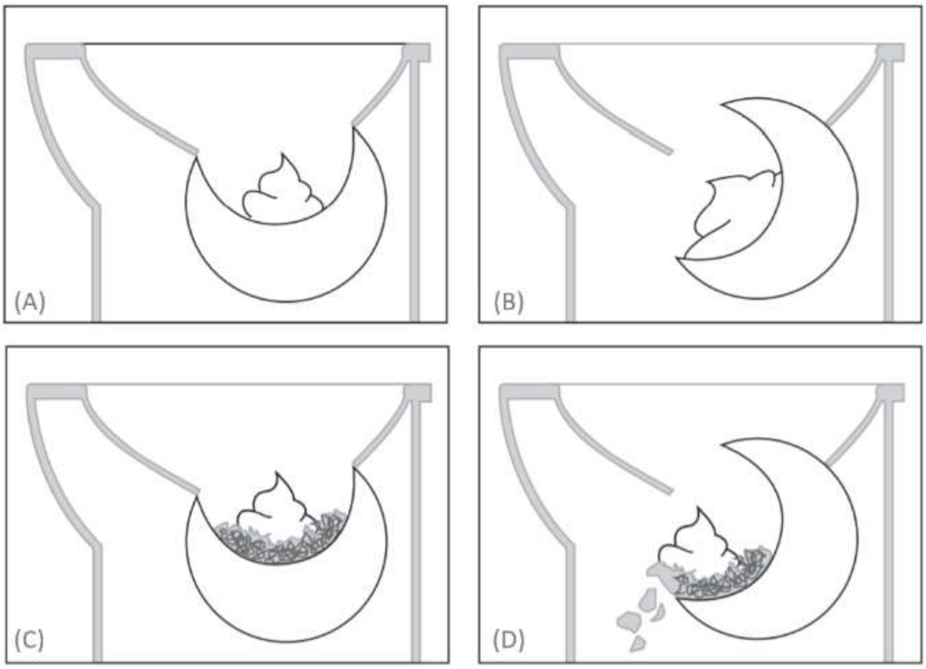


Figure 75 - Diagram describing how the sawdust prevents surface fouling. A & B depict faeces landing into the rotating bowl and adhering to the surface through rotation. C & D show how the sawdust acts as a sacrificial layer so there is no surface contact (Tierney, R. 2017)

The group selected was an ‘off-grid’, eco-community called ‘Transition Heathrow’ who live on a reclaimed area of unused land covering approximately four acres. They believe in resource autonomy and practice a self-contained, self-sustaining way of life by building infrastructure from discarded refuse and growing all of their own food. The toilet facilities on site comprise of two Urine Diverting Dry Toilets (UDDT) allowing faeces to be composted and stored before being used as fertiliser for their crops. Ecological sanitation such as this imitates healthy ecosystems found in nature turning a waste product into a valuable resource (Esrey, 2001). As shown in Figure 76, the toilets were raised off of the ground to allow for a 240 litre wheeled bin to be placed directly under the toilet seat. The user would take a handful of sawdust and drop it into the bin after they have defecated, facilitating the composting process by improving the carbon-nitrogen ratio and helping to reduce odour (Lopez Zavala and Funamizu, 2006). Once full of excreta, the bin is removed and stored for the decomposition to take place transforming it into compost for future crop growth. A new empty bin is placed under the raised toilet and the process repeated.

Figure 76 – One of the two raised toilets that the eco-community have built and use with one of the residents demonstrating storage and processing of the excreta (Tierney, R. 2017)

The UDDT currently in use at the site has a standard toilet seat on a wooden structure shown in Figure 77. The RWF could be retrofitted to the wooden structure easily and would be in line with the community's position on simple technology. The RWF would have to be securely fixed to the wooden structure otherwise lifting up the lid would lift the whole mechanism but that would be an easy task. From a behaviour perspective, the RWF would perform better if the user was to drop sawdust into the bowl before use to reduce fouling. This is in the different order to how the community currently use the UDDT whereby they drop sawdust into the toilet after defecation.

Figure 77 – (A) The toilet area and (B) the view inside of the UDDT at the eco-community **(Tierney, R. 2017)**

5.3.2 Questionnaire design

To assess the potential of the RWF with this secondary target market, a questionnaire was used. The purpose of this questionnaire was to elicit user attitudes to their current toilet and their thoughts towards the RWF. The questionnaire design followed the rationale of Judge et al. (2015) by using a two-stage questioning method and was piloted on three people who had experience with composting toilets. The first page had three questions, then there would be a demonstration of the RWF, followed by the respondents answering a further three questions relating to the RWF. This is shown in Figure 78 and the full question is in A.9

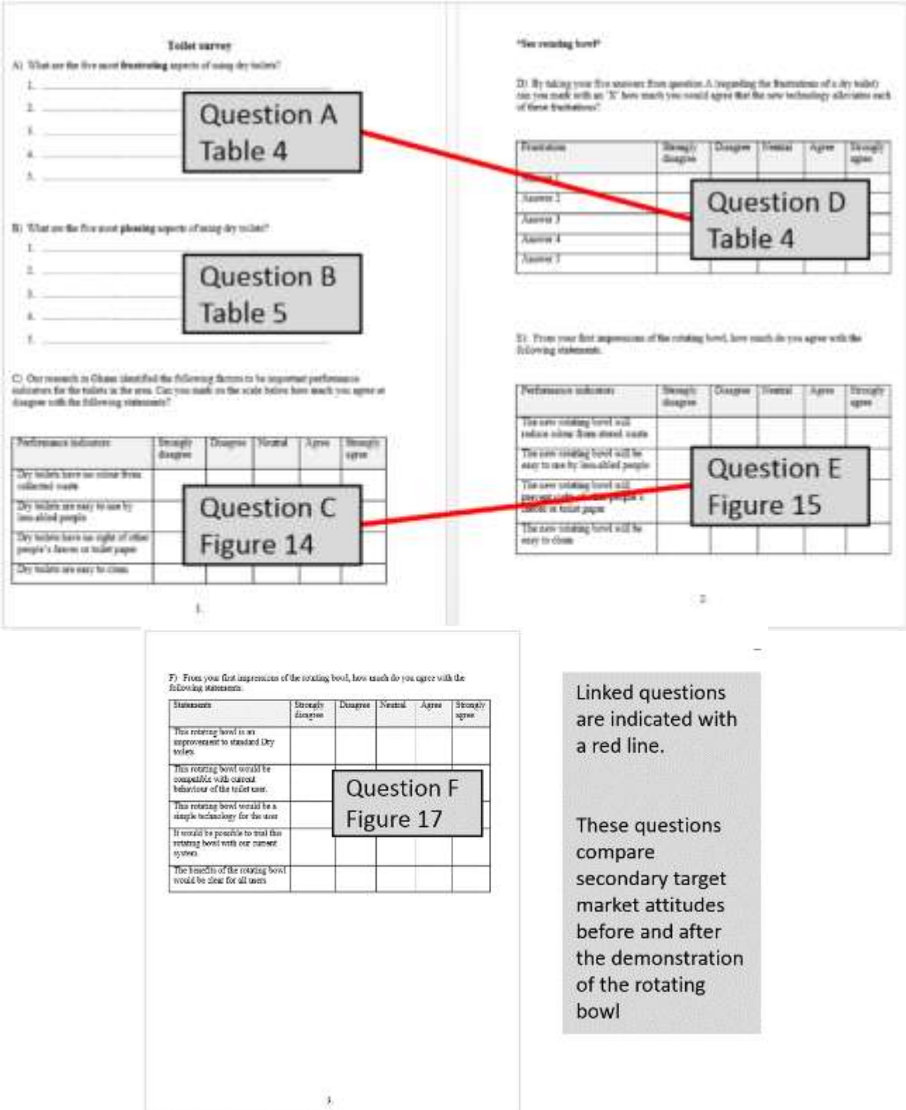


Figure 78 - Questionnaire used with secondary target market group. Red lines indicating linked questions (Tierney, R. 2017)

The first page of the questionnaire was to gain an understanding of the current user experience and attitudes of the eco-community with questions related to their current UDDT. To do this the first two questions (A & B) ask them to describe the five most frustrating aspects of using UDDT followed by the five most pleasing aspects of using a UDDT. The third question (C), was comprised of four stem statements to be answered with a Likert scale to describe how strongly they agreed with each statements. The stem statements were informed by research in the primary target market of Kumasi and were based on the four concerns expressed by the inhabitants. These statements were 'dry toilets have no odour', 'dry toilets are easy to use by the less-abled', 'dry toilets have no sight of other people's faeces or toilet paper', 'dry toilets are easy to clean'. The group were instructed to not turn over the page once they had answered the third question and to wait for everyone to reach that point. The RWF was then demonstrated with sawdust and soybean paste and the respondents began the next set of questions. The layout of the questionnaire and how early questions linked with questions after the demonstration can be seen in Figure 78. Question D asked the respondents to take their answers from question A ("what are the five most frustrating aspects of using dry toilets?") and consider how strongly they believe the new RWF would alleviate each frustration, once again using the Likert scale. For example, respondent four answered 'mosquitos and flies' as being a frustration with the dry toilet they currently use and they '*strongly agreed'* that the RWF would alleviate this frustration. Question E asked how strongly they believe the RWF could alleviate the concerns raised in Ghana. This would compare against how well they thought their current UDDT addressed these concerns asked in question B. The final question was based on Rogers's characteristics of adoption as to assess how likely the RWF would be adopted by the group. Figure 79 shows the eco-community during the session, with the prototype in the middle of the group.

Figure 79 – Prototype demonstration at eco-community (Tierney, R. 2017)

5.3.3 Results from questionnaire

The results from the questionnaire are now be presented not in the sequential order of the questionnaire but instead by how the questions are linked. As the results from questions one and four are linked, Table 19 combines both sets of answers. Individual respondent answers show they '*strongly agreed'*[22] that five of the frustrations could be improved with the RWF and all of these were associated with the user experience. Further examination of the results was conducted by two researchers, grouping the answers into five prominent subjects. Identifying key and grouping subjects from the results is a method in the Human-Centred Design field guide that allows for deeper insights to be gathered from a set of data (IDEO.org, 2015). From the results, **'User experience'**[23] causes the most annoyance with 16 different frustrations recorded compared to 12 for the combined **'Process'** frustrations. **'Sawdust'** and **'storage of excreta'** were the cause of six frustrations each but can be seen as both being part of the **'process'** of the UDDT system. The second most frequent subject recorded was to do with sawdust so there is potential for improving the experience of using composting toilets if this aspect can be improved. Some answers could be interpreted that there was some confusion as to what to select if there was no relation or the bowl can have no relation for example "can be smelly" and "There's no light" were both given *'neutral'* responses.

[22] The user response will be indicated with *italicised text.*
[23] Subjects will be indicated with **bold text.**

Table 19 - Responses to Questions 1 & 4; (1) The frustrations with using the current composting toilet and (D) the extent to which they agree the rotating flush can improve each frustration with key below

Subject	Respondent	Frustration with current dry toilet	To what extent do you agree the RWF can improve this frustration?
16 Frustrating aspects relating to the: **User experience**	3	“smell”	5
	2	“Less luxurious”	5
	3	“Sight of other people poo”	5
	4	“Mosquitos and flies”	5
	8	“Not clean or very cleanable”	5
	4	“Knowing it is easier to spread disease”	4
	4	“Stuff can get dried and stuck on the sides. General build up.”	4
	9	“Menstrual waste and urine have to be separate”	4
	6	“Faeces getting stuck to the sides”	4
	6	“Separator not working properly”	4
	10	“Not designed to be cleaner friendly”	4
	2	“Can be smelly”	3
	7	“Keeping clean”	3
	10	“Blocked separator”	3
	1	“People not ‘flushing’ with sawdust”	2
	8	“No space for non-faecal waste”	2
6 frustrating aspects relating to the: **Process-Sawdust**	4	“Picking up sawdust how much to throw on”	4
	11	“Sawdust everywhere”	4
	8	“Sanitation - mess caused by sawdust etc. contact with hands”	4
	4	“Focus goes on sawdust, not on maintaining toilet paper”	3
	9	“Touching sawdust with hands/spillage”	3
	6	“Having to add a handful of sawdust”	2
6 frustrating aspects relating to the: **Process-Storing the excreta**	7	“Having to empty”	4
	2	“It's better if it's emptyable rather than a hole in the ground”	3
	6	“Having to change them” [the storage container]	3
	6	“Having to change container”	3
	5	“Creating and maintaining the useful poo aka the 'product'”	2
	10	“Requires pit or elevated structure”	2
4 frustrating aspects relating to the: **Location**	8	“Distance from nest of site/high sites”	3
	9	“Sometimes our toilet feels left private”	3
	7	“Normally far away from living area”	2
	2	“It's outdoor”	2
	8	“There's no light”	3

6 frustrating aspects that were not specific	9	"Toilet paper doesn't always feel "clean enough"	3
	10	"Lack of maintenance"	3
	11	"Sometimes no toilet paper"	3
	10	"Uncertainty about pathogens"	2
Hand washing	7	"Normally no water to wash hands"	3
	9	"Sometimes we lack hand wash"	3
	2	"No sink/running water"	2

Strongly disagree	Disagree	Neutral	Agree	Strongly agree

Subject grouping (IDEO.org, 2015) was also utilised for the pleasing aspects presented in Table 20. The highest number of Pleasing responses were grouped under '**Process'** and in particular the knowledge that they practicing sustainable sanitation with no impact on the environment. There is some uncertainty in the grouping as some of the comments designated '**Unspecified'** could refer to either the user interface or the **'User experience'** or the **'Process'**.

Table 20 - Answers to Question B) The most pleasing aspects of using a UDDT

Subject	Respondent	Pleasing aspect
18 pleasing aspects relating to the: **Process**	4	"You tend to know where your excrement goes"
	5	"You can turn your poo into a usable object - not seeing it as 'waste'"
	6	"Knowing the waste product can be used"
	9	"Understanding use of urine and faeces as compost/resource"
	9	"Never having to fix plumbing"
	11	"Reusing the waste e.g. fertiliser"
	11	"Knowing not wasting water"
	11	"Knowing not polluting the environment e.g. Chemicals used to treat sewage
	11	"Knowing not wasting energy"
	2	"Have learned about the breakdown of humanure"
	2	"Can be good for the environment"
	3	"Environmentally friendly"
	3	"Knowing the amount of carbon will be greatly reduced"
	1	"Not wasting valuable resources"
	7	"Being able to compost"
	8	"It turns to compost"
	1	"Not wasting valuable resources"
	4	"Doesn't smell like chemicals normally"
	4	"Not having to touch a flush handle, generally feels cleaner"

12 pleasing aspects relating to the: **User Experience**	5 5 6 6 9 7 7 8 9 9	"No splash" "Smells better most of the time (if maintained properly)" "No splash" "Very little sound" "In general much less disgusting" "Having a squat position toilet" "No chemical smell" "It's quiet" "Faeces less visible/smelly" "In general much less disgusting"
Unspecified	6 10 9 1 2 2 8 7 8 2	"No use of water "No water consumption "No leakage "The height of the long drop gives lovely views "Is a novelty at times "Less shit everywhere/more controlled "It doesn't really need fixing "No chemical smell "No chemical smell 'Better than seeking a tool to dig a hole'

Question C was based on the four primary issues that were uncovered during primary research in Ghana (Objective Two) and how well they feel their current composting toilet performs against each issue. These stem questions involved 'malodour', 'ease of use by less abled', 'no clear sight of the waste from other people' and 'ease of cleaning'. A Likert scale using stem statements to be agreed or disagreed with, was chosen as using a performance statement can be interpreted as being more subjective (Johns, 2010). After this question there was an interlude as the RWF was shown to the group and a demonstration of use with Soy bean paste was performed. The secondary target market group were then asked to continue with the questionnaire. The answers were transferred into numerical results by assigning *'strongly disagree'* as 1.0 and *'strongly agree'* as 5.0 therefore the higher the result, the better the toilet performs in regards to that question. For question C, the general response to the UDDT is '*neutral'* (3.0). There is a slight positive opinion that there is no odour and that dry toilets are easy to clean but the other two factors are negative. 'Dry toilets have no sight of other people's faeces or toilet paper' is the lowest scored with 2.5 indicating that, overall, the group disagree with statement however this answer had the highest standard deviation out of all answers meaning there was a great deal of variation in responses. A vertical line is used to indicate the results from each stem question and a 'dashed' horizontal line is to improve clarity for the reader.

Dry toilet	Average	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	Standard deviation
Dry toilets have no odour from the collected waste below	3.4						1.13
Dry toilets are easy to use by less-abled people	2.8						0.98
Dry toilets have no sight of other peoples faeces or toilet paper	2.5						1.36
Dry toilets are easy to clean	3.2						1.27
Average	3.0						0.97

Figure 80 - Results of Question C

After the RWF demonstration, the group had to answer the questions based on the Ghanaian frustrations but with considering how well they would expect the RWF to reduce these frustrations. The RWF was expected to perform better on all factors by the group. The group agreed that 'the new RWF will prevent sight of other people's faeces or toilet paper' showing the greatest shift in comparison to the UDDT.

Rotating bowl	Average	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	Standard deviation
The new rotating bowl will prevent odour from collected waste below	3.6						0.81
The new rotating bowl will be easy to use by less-abled people	3.8						0.40
The new rotating bowl will prevent sight of other peoples faeces or toilet paper	4.2						0.65
The new rotating bowl is easy to clean	4.0						0.77
Average	3.9						0.37

Figure 81 – Results of Question E

By comparing the individual answers in some points of interest can be extracted. Figure 82 takes an average score given by each respondent to questions related to their current UDDT and the RWF to allow for comparison. Respondent one '*strongly agreed'* with all positive statements about the composting toilet indicating someone who is very happy with the UDDT. Respondent one also only gave one frustration, "people not flushing with sawdust" which could arguably be more a frustration with his fellow users than with the UDDT. All respondents except respondent one and respondent nine, gave answers expecting the RWF to perform better than their current UDDT in relation to the frustrations encountered in Ghana. Respondent two and respondent eight had the greatest difference in favour of the RWF and only respondent 10 gave equal answers.

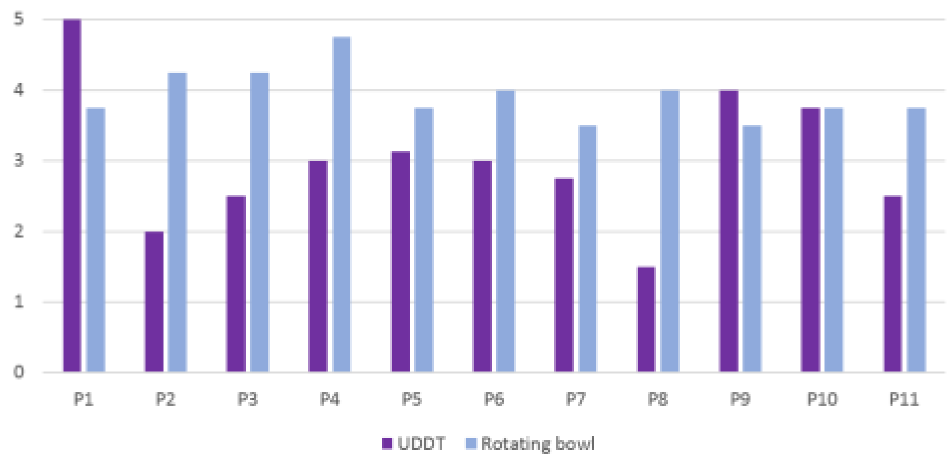


Figure 82 - Averaged response given to both the dry toilet and the RWF by each respondent

From a mechanical perspective, the rotating flush could be modified through minor design alterations to be retrofitted to the UDDT at the Eco-community. The user adoption is often the bigger challenge due to existing beliefs and ingrained behaviour. Everett Rogers seminal work on the adoption of innovation (2010) identified five characteristics that increase the likelihood of adoption by a target user. These characteristics are;

- *Relative advantage* – The degree to which the innovation is perceived as better than the idea that precedes it.

- *Compatibility* – The degree to which an innovation is consistent with existing experiences and needs of potential adopters.
- *Complexity* – The degree to which the innovation is perceived as difficult to understand and use.
- *Observability* – The degree to which the end results of the innovation are visible to others.
- Trialability – The degree to which the innovation may be experimented with.

These five characteristics were used as the basis for stem statements in question F to assess the new RWF and likelihood of adoption. Using Rogers' characteristics of adoption is a respected and well used starting point for discussing the potential for a product and was used in the testing of another waterless toilet system on funded by The Bill and Melinda Gates Foundation, The Blue Diversion Toilet (Tobias et al., 2017). The overall response to these Likert scales fell just below the '*agree'* option with 3.8. From 11 respondents answering five questions each, only two responses '*disagreed'* with any factors relating to the adoption of the bowl and none were marked as '*strongly disagreed'*. Whereas almost half of all answers (25/55) '*agreed'* with the statements and 11 '*strongly agreed'* which is very positive. There were two stem statements that the overall group '*agreed'* with and those were "the RWF is compatible with current behaviour of the toilet user" and "The RWF would be a simple technology for the user". These statements are consistent with early requirements from the design brief to not change user behaviour but instead utilise user behaviour. This resulted in the RWF being driven by closing the lid after use.

Statement	Average	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	Standard deviation
This rotating bowl is an improvement to standard dry toilets	3.5						0.82
This rotating bowl is compatible with current behaviour of the toilet user	4.0						0.83
This rotating bowl would be a simple technology for the user	4.0						0.89
It would be possible to trial this rotating bowl with your current system	3.9						0.70
The benefits of the rotating bowl would be clear for all users	3.5						0.68
Average	3.8						0.45

Figure 83 - Results of Question F

This can be seen as an overall positive test where a number of key points of interest have been gathered. The overall consensus of the secondary target market group is that the RWF improves upon their current composting toilets and is compatible with their current practice.

5.3.4 Focus group discussion

Focus groups are often used by companies and marketers to gather insights and gauge opinions from a carefully selected group of participants (IDEO.org, 2015; Martin and Hanington, 2012). Once the questionnaires were completed, the discussion between the group and the researchers was recorded and prompted by a few key areas of interest to assess viability of the secondary target market for the rotating flush. The majority of the discussion was answering the group's questions as they were highly engaged and very familiar with using waterless toilets.

After the questionnaires had been completed, key questions and comments in open discussion were recorded:

- *“The toilet has to be redesigned as a urine diverting toilet. Composting toilets that have urine and faeces together will smell considerably worse than no-mix”*
- *“How does the toilet pan (non-rotating section) stay clean if it is not swiped clean”?*
- *“Can sawdust be loaded automatically as a few of our residents have irritable bowel syndrome and having to preload the sawdust could cause distress”.*
- *“Can the rotating bowl fit on any composting toilet?”*
- *“How much would it cost?”*
- *“How easy is it to fix”.*

Figure 84 - Focus group discussion

5.3.5 RWF UDDT redesign

Transferable technology can be based on a core product architecture that can be interchanged or upgraded for different markets (Judge, Hölttä-Otto and Winter, 2015). Developing a new version of the RWF mechanism to meet the needs of the secondary target market would not be very difficult. The core feature of the component is the rotating bowl and swipe blade which would be integral to any redesign. A reshaped pan incorporating a small divider that could be modelled on the dimensions and shape of existing urine diverting pans would be the primary design alteration and would direct urine to a hose for separate storage. As urine contains 80% of the nutrient excreted by humans this could be put to use quickly and effectively to improve crop growth for the community (Moe and Rheingans, 2006). Blocking of the urine diversion hole on the current UDDT was a frustration recorded from the eco-community, so the new urine diverting pipe would have to be easy to access, clean and unblock. A plastic grate cover can also be developed if this problem is also noted in the new UDDT RWF.

The RWF design for the NMT incorporated an odour seal that was only engaged when lid was fully opened or closed. The drum lowered by 2mm during the first part of rotation and would raise and seal during the very last part of the movement. This is an important feature for the NMT as the holding tank would hold mixed human waste that would produce considerable malodour. Separating the urine and adding sawdust reduces odour, therefore the UDDT RWF can potentially be simplified further by having just a normal gear configuration.

Figure 85 - CAD model of redesigned urine diverting dry toilet for composting communities (Tierney, R. 2017)

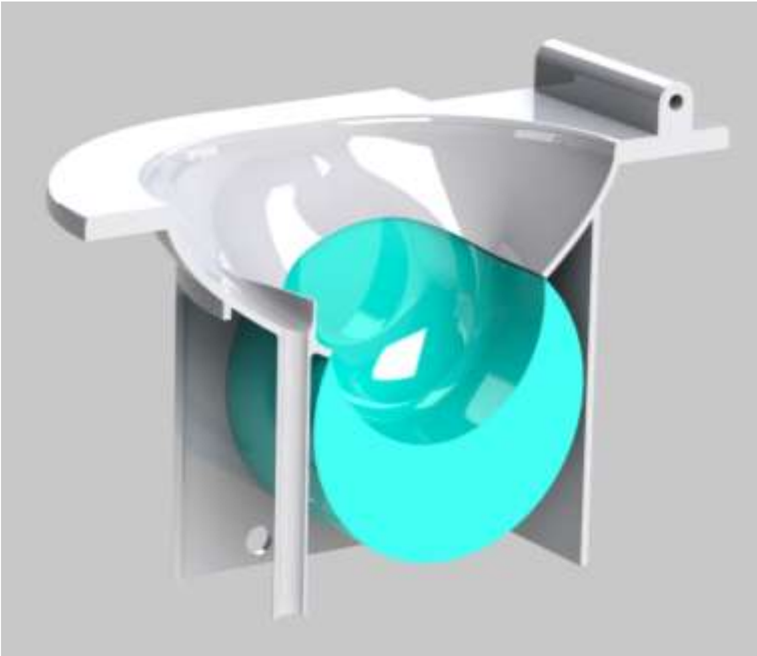


Figure 86 – CAD model cross section of redesigned urine diverting toilet pan (Tierney, R. 2017)

5.4 Chapter analysis

This chapter profiled the testing of the user interface prototype and assessed the potential for the RWF to be adopted by a secondary target market. The first key outcome of the chapter was confirming the prototype as being able to transfer and store the average excreta of seven people over the course of two days which is the basic function of the RWF. One clear issue that would lead to a poor user experience was with bowl fouling when faeces entered the bowl before urine. The original swipe blade used in this testing does not appear to apply sufficient force on to the bowl surface to completely clean the bowl surface. The pan shape does not appear to be optimal as urine collects on the edge. Odour being transferred from the holding tank when opening the lid was noted by the researchers as a cause for concern. Preventing odour and sight of excreta are crucial aspects of ensuring a good user experience.

The second key outcome of the chapter was the first users testing of the toilet prototype with overall positive feedback recorded. Positive responses were noted with particular focus appearance and similarities to normal flushing toilet. The lack of flush handle and just closing the lid was referred to as being novel and intuitive. Negative comments referred to the force required to close the lid and an unclean toilet from previous users. The negative responses caused by sight and smell of previous users confirmed the concerns raised during simulation testing. The force required to use the toilet was an unexpected frustration.

The third key outcome was the positive feedback and compatibility of the new waterless toilet technology with a secondary target market. Eight out of eleven focus group members answered indicating they expect the rotating flush to improve the frustrations noted from the primary research in Ghana. A point of interest when considering adoption of a UDDT can be inferred from the grouped, collective results of 'pleasing aspects' and 'frustrating aspects' of using a UDDT. When asked about their frustrations with the UDDT, the majority of these were in relation to the user experience. Compared to when they about the aspects they do like about the UDDT the majority of these were related to the process. To encourage the adoption of UDDT, future projects should look to address the frustrations and emphasise the desirable aspects.

Another target market who could benefit from the RWF is the ecotourism sector that also advocate environmental stewardship. A section in the book '*Ecotourism: Principles and Practicalities'* (2009) states the following in regard to sanitation:

> *"As the adventure travel and ecotourism sectors have grown, operators have offered higher and higher standards of service in competition for clients, particularly more wealthy clients. Since toilet facilities have often been perceived by clients as the low point in the facilities provided, there is considerable incentive to invest in more comfortable system"* (Buckley, 2009).

The ecotourism market could potentially provide the financial incentive for toilet manufacturers to invest in waterless toilets with similar constraints to developing countries. The wealthier clients referenced will almost certainly be used to the flushing toilet and be accustomed to the ‘flush and forget’ pleasant experience the technology provides. However they also enjoy and are willing to pay to travel to places where flushing toilets are not practical or where the environment is valued.

The improved understanding of user testing, user acceptability and the attitudes towards various toilets has been used to inform the user groups for future testing[24]. The testing was changed from an original public facility that uses flushing toilets to household toilets previously using pit latrines. The RWF is still early in development and should not be compared to a normal flushing toilet yet, but instead against waterless toilets. The aim is to be able to compete with flushing toilets eventually but whilst still early in development user expectations should be careful considered.

5.4.1 Limitations

The development and testing of the cleaning swipe blade in Objective Three was not completed in time for inclusion into this testing. Instead, the existing swipe blade was used that is made from a low cost flexible polymer instead of silicone as recommended and was not in the optimised shape and size.

Project restrictions limited the testing that was initially planned for this Objective and had a considerable impact on outcome. One week of testing of the RWF by a secondary target market group was scheduled and agreed by senior project leads but prohibited due to updated testing concerns from the sponsor shortly before testing was due to take place. Poor user testing could reflect badly upon

[24] The location for this testing will be in Africa but with the actual location undisclosed due to the high-profile and confidential nature of the project.

the sponsor and was therefore restricted. Only affiliates of the university were permitted to use the user interface for real-use testing and only carefully selected external testers would be allowed to take part in demonstrations provided a non-disclosure agreement was signed. Online demonstrations and questionnaires were also prohibited for the same reason. To aid negotiating a test plan a matrix was produced featuring the various combinations of testing that could take place. The ideal testing would involve a secondary target market using the toilet for an extended period of time to observe the user in the natural surroundings, in-line with ethnographic research methods that value natural behaviour (Goffin, Lemke and Koners, 2010). Due to these reputation concerns, additional secondary target market testing was prohibited. The demonstration and discussion with the eco-community had already been conducted before this issue arose.

Table 21 - Secondary target market user testing group option list

Preference	Location	Testers	Time frame	Method	Expected number of testers
1	Campsite	Members of secondary target market	2 days	Given to user to use in their own environment	20
2	Festival	Expert of products for secondary target market	1 day	Used once then cleaned after each use	50
3	On campus (in context)	Sanitation experts	One day event	Mock demo (e.g fake urine and faeces)	5
4	Campus (3rd floor Vincent building)	University staff	One day event	Comparison test vs existing toilet	<5
5	Online	Caravan club. Technology board members	1 week	Video of demo (e.g fake urine and faeces).	7
6	Online	SuSanA forum members	1 week – data collection 2 weeks analysis	Comparison test vs existing toilet using video demonstration	Unknown (likely more than 20)

5.4.2 Recommendations for future work

- It would be advised that larger trials involve people of varying physical abilities as a main trigger for acquisition in Ghana was for elderly relatives.
- Identifying a tertiary target market could add a new aspect to understanding the transferability of waterless toilet technology.

5.5 Chapter Five highlights:

The prototype of the user interface was able to perform basic function for two days' worth of simulated use with seven users but surface fouling is a concern when faeces enters bowl and using old swipe. Positive feedback was recorded during user testing after seven people used the toilet for two days. Some of the same user frustrations recorded in the secondary target market were identified as in Primary target market Kumasi. Overall, positive feedback was also given from the secondary target market suggesting the technology has potential application in a secondary target market. The following chapter will now synthesise all of the key findings from the thesis and identify key themes.

“Design, if it is to be ecologically responsible and socially responsive, it must be revolutionary and radical”.

Victor Papanek (1982)

6 DISCUSSION

This Chapter will explore key themes from each Objective and use multiple sources from the research to discuss relevance and impact on the Research Question. Figure 87 visually depicts the structure of the Discussion, starting with a description of how the different Objectives link and build on the previous to arrive at the Conclusion. The key themes of each Objective are then discussed using evidence from throughout the research to examine the statement. The chapter will conclude by discussing the strengths and weaknesses of reverse innovation for improving sanitation and areas for future research.

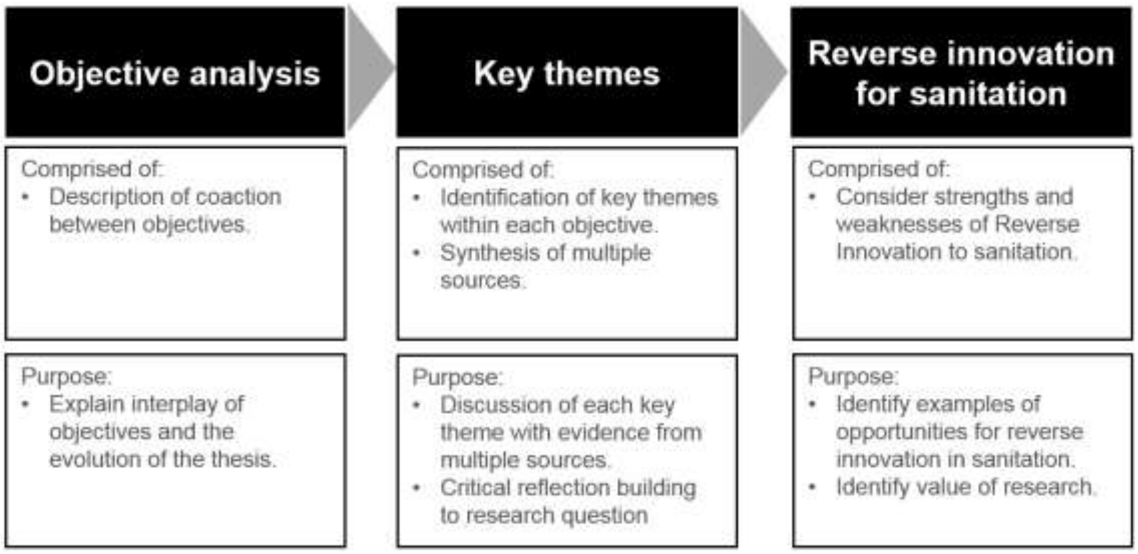


Figure 87 - Diagram showing stages of discussion and outcome of each part.

6.1 Objective connections

Each Objective was intended to act as a standalone piece of research that would also combine with the other Objectives to form a thesis greater than the sum of its parts. The Objectives were logically structured in order to evolve the topic and conclude with a rational and balanced answer to the research question. The interplay of the Objectives can be briefly summarised as the following: Objective One reviewed different levels of toilet technology with a focus on user experience. Kvarnström's (2011) updated sanitation ladder was used to examine the various technology in use around the world. Objective Two examined the people who have to use the different toilet technology. The residents of Kumasi, Ghana were profiled gaining insight on their behaviours and attitudes towards toilets as well as reasons for adoption. Objective Three detailed the development and testing of a waterless toilet technology designed to improve the user experience of various toilets mentioned in the literature review (Objective One) and observed in Kumasi, Ghana (Objective Two). Key considerations for the innovation path were detailed to inform future designers and engineers of waterless toilet technology. Finally, Objective Four explored the potential that the Rotating Waterless Flush (RWF), designed for Kumasi Ghana, could improve the user experience for a secondary target market.

6.2 Objective key themes

Each Objective will now be declared with the emergent themes being discussed using multiple sources of evidence. This approach to the Discussion was chosen to emphasise the importance of each Objective and how key findings have informed the answer to the research question.

6.2.1 Objective One: To review literature surrounding low-water sanitation options with a focus on the user experience.

The Objective was to review literature on existing toilet user interface technology with a focus on user experience. Kvarnström's revised sanitation ladder (2011) was used to structure the review with examples of key technologies evaluated at each point. The user experience of the different technologies was considered and recommendations for improvements were made.

Key theme A: The approach to monitoring and improving global sanitation has to be improved.

The UN sanitation Ladder (UNICEF/WHO, 2008) is the recognised method for monitoring sanitation access by grouping the world's population into one of five categories depending on what toilet they use. This has been criticised as being too simplistic and not taking into consideration the environmental impact (Kennedy-Walker et al., 2014). Kvarnström's (2011) updated sanitation ladder focusses less on the individual technologies used and instead on the benefit provided. The seven levels of the updated ladder are comprised of four health factors as the lowest levels and three environmental factors as the top levels. It would be advisable that new toilet technology is designed to adhere to the specific attributes of Kvarnström's ladder to ensure that both health and environmental factors are addressed. Improved toilets that reach the highest levels of the ladder and ensure resource recovery will be hugely beneficial as population in urban environments increase (WHO, 2016). Kvarnström correctly acknowledges the importance of user experience that can often be missed when describing sanitation. The author states; "the pleasantness of the user experience with a sanitation system can be a determinant of whether it is used properly, and thus whether it is providing the necessary benefit or not". Objective Two explored this in detail to emphasise the user at the various sanitation levels. There were 24 observations for disease recorded during the systematic observation sessions during the footage from Ghana. Of these codes, avoiding disease was a driver of acquisition for the Clean Team Toilet with one example of a responder being;

“you get diseases from public toilet, but clean team uses chemical” (respondent 74). It can be inferred that by promoting avoiding disease will increase adoption of improved toilets but moving higher up Kvarnström’s ladder into the environmental factors, may be less direct. ‘Environmental benefits’ were not identified as drivers sanitation adoption and will not likely encourage people to progress up the sanitation ladder (Jenkins and Sugden, 2006). Instead, improved social standing as well as convenience were the main drivers and need to be at the heart of new waterless toilet systems. The toilet technology that is needed for the future of urban environments will have to be designed to combine the technology required for the higher levels of Kvarnström’s sanitation ladder whilst addressing the reasons for adoption noted by Jenkins and Sugden.

Key theme B: There is a need for improvements to toilets across whole sanitation ladder.

Billions of people at the Bottom of the Pyramid (BoP) lack access or have poor user experience (Bartram et al., 2010; Black and Fawcett, 2008) and the top of the economic pyramid, users of flushing toilets rely on unsustainable amounts of water to transfer their excreta (Langergraber and Muellegger, 2005; Teh, 2013). Frustrations and areas for improvement towards the user experience were identified at all levels of the sanitation ladder. Flushing toilets use unsustainable amounts of water but are the most desirable. Composting toilets are environmentally excellent but are highly unlikely to be adopted by people other than those who strive for an eco-way of life or live in a remote location such as Swedish countryside (West, 2001). Pit latrines are the cheapest way of having a toilet and the most abundant in the developing world but are not desirable and can smell (Obeng et al., 2015). Public toilets offer sanitation to those in densely populated slums but it is unsafe to leave the house for females, undignified, inconvenient and often poorly maintained. Open defecation has cultural and traditional ties which can be broken through behaviour change techniques such as CLTS but there needs to be low cost alternatives for people to adopt instead

(Sah and Negussie, 2009). Table 22 draws on evidences from Objectives One, Two and Four.

Table 22 - Compilation of toilet user interfaces throughout thesis reviewed with user frustrations and the environmental issues of each one

Technology	Examples of user frustration	Potential environmental issues
Private Flushing toilet	Surface fouling. The latest high-tech toilet from TOTO Ltd uses a complex system of electrolysed water and UV lighting to clean the surface, indicating surface fouling is an issue (Belussi and Orsi, 2015).	A person using a flush toilet will on average use 15,000 litres of water per year. This is an unsustainable amount (Werner et al., 2000).
Composting toilet	"Less luxurious" (Eco-Community Respondent 2). Users having to be more active in their waste management and the perception they are a poor alternative can be barriers to acceptance (Anand and Apul, 2014).	Space can be an issue of composting toilets in urban environments as well as flooding leading to environmental pollution (Katukiza et al., 2010b).
Clean Team sawdust	"Sawdust is good but children make a mess [with it]" (Ghanaian Respondent 59)	No major issues provided effective collection and responsible processing. Toilet collection service utilising composting is a proven method in other urban communities (Auerbach, 2016; Rao et al., 2016).
Clean Team chemical	"Splashing of liquid" (Ghanaian Respondent 49). The odour of the chemical was coded as a frustration by 12 different Ghanaian respondents with an example being Ghanaian Respondent 13: "The smell (of the chemical) gets in the clothes".	Chemical used (glutaraldehyde) is not biodegradable and would interfere with any secondary processing method (Narracott and Norman, 2011) (David, 2014)
Unimproved private household pit	Insects that can travel into and out of the pit can transfer disease. (Bartram et al., 2010)(Guiteras et al., 2015)	Poorly built pit latrines can leach contaminates into ground water (Dzwairo et al., 2006).
Flushing shared	Having to walk to a public toilet constitutes an unimproved toilet (Exley et al., 2015). Women in particular are at risk from walking to a toilet at night (Arku, Angmor and Seddoh, 2013).	Uses 9 litres of water per use and will be used by many residents throughout the day (Dixon, Butler and Fewes, 1999) (Braun et al., 2003)
Unimproved shared	Fear of contracting 'white' (*candidiasis*) from the 'heat' that comes off of other people's excreta in the pit latrine. (Ghanaian Respondent 45) (Jenkins and Scott, 2007)	Poorly built pit latrines can leach contaminates into ground water (Dzwairo et al., 2006).
Chamber pot	"Using chamber pot attracts flies" (Ghanaian Respondent 36)	Chamber pot is only a convenient receptacle. The environmental issues would depend on how the excreta is finally disposed of.
Open defecation	Risk of attack mainly for females (Mara et al., 2010a)	Contamination of water sources (Bartram et al., 2010)

To summarise the main issues: there is unpleasantness from using a dirty toilet, there are less-visible risks of disease transfer via the faecal oral pathway and there are concerns for environmental degradation due to polluted/wasted water. There is one issue which has to be improved upon to have an immediate improvement on dignity and personal safety and that is the lack of household toilets. During the primary research in Kumasi, Ghana, (Objective Two) residents explained that public toilets are the only option that they have when they need to carry out one of the body's basic functions. The fear that women have of being attacked whilst walking to a public toilet was distressing to hear (Ghanaian Respondent 54: "finds it scary to go to the toilet at night" Ghanaian Respondent 22: "fear of using the public toilet at night, scared someone could attack me"). The vulnerability of females visiting the public toilet at night is certainly not only isolated to Kumasi and has been reported in literature and news stories (Anand and Apul, 2014; Arku, Angmor and Seddoh, 2013; Kwiringira et al., 2014). Self-contained sanitation gives a suitable option and there are successful collection service toilets in use in various locations[25] around the world today but there are countless communities that remain unserved.

Designing new resource constrained toilet technology for the poorest people in the world can produce a successful innovation to improve lives. The features of this innovation can also meet the needs of a niche group in the developed world becoming an example of reverse innovation.

6.2.2 Objective Two: To identify and analyse the frustrations and perceptions associated with using different toilets by residents in Kumasi, Ghana (the project's primary target market).

[25] Such as; Clean Team in Ghana(Narracott and Norman, 2011), SOIL in Haiti (Rao et al., 2016), Sanergy in Kenya (Auerbach, 2016).

By profiling the existing technology and behaviour of the primary target market, a rich understanding developed of the how community live without widespread access to flushing household toilets. Personas were created for common examples of people within the community, at each level of sanitation.

Key theme A: Repulsion to excreta is human instinct but nuanced.

In many cultures the act of defecation is one of, if not, the most private act. The subject is cloaked in euphemism, used as a joke or ignored altogether (Van Der Geest, 2002). In the appropriately titled book *The Last Taboo*, Black and Fawcett (2008) “the subject of human waste is rarely aired. We talk about ‘water-related’ diseases when most are sanitation-related – in short, we don’t mention the shit”.

Using semi structured interviews in Kumasi, Ghana the respondents were able to discuss the subject of toilets with more freedom than a conventional survey or other less intensive research methods (Goffin, Lemke and Koners, 2010). This approach allowed the issue of ‘heat’ to be identified and explored further by the interviewers. ‘Heat’ is believed by residents to rise off of other people’s faeces and carry disease, specifically causing ‘white’ (*candidiasis*). The fear of heat was expressed by eight residents and has been recorded previously in literature by Jenkins and Scott (2007). The belief of faecal odour causing contamination of the air and disease has existed since ancient times and is a reason some people still prefer to openly defecate rather than use a latrine (Rheinlander et al., 2013). Stevenson and Repacholi (2005) found that the repulsion caused by visceral stimuli such as faeces is greatly increased when the excreta is not one’s own or that of a close family member. This also congruent with the statement by the mother who feels there is less chance of contracting disease using her Clean Team toilet as it is only her and her daughter using the toilet (Ghanaian Respondent 07). In the book ‘The Great Taboo: opening the door on the Global sanitation crisis’ acknowledges odour as not readily featuring during the discussion of sanitation policies and planning but this is at the heart of all efforts to improve sanitation (Black and Fawcett, 2008). The sight and the smell of other people people’s excreta is a universal stimulus of disgust and cause of a visceral reaction. Faeces is considered the most unpleasant of odours to humans and a prominent stimulus for disgust and repulsion (Afful, Oduro-Kwarteng and Awuah, 2015). During the interviews of residents in Kumasi, Ghana, 20 observations coded as frustrations were due to smell. Interestingly, 14 of these were caused by the chemical used in the Clean Team toilet to mask the smell (for example Ghanaian Respondent 17 "the smell of the chemical is very strong"). The remaining seven coded frustrations were caused by the odour when visiting public toilet. From the testing with a secondary target market (Objective Four), of the 11 respondents, two identified odour as being a frustration of the UDDT (Eco-Community Respondent 03 "smell" and Eco-Community Respondent 02 "can be smelly"). Three respondents noted the sight of other people's faeces as being frustrating such as "Faeces getting stuck to the sides" (Eco-Community Respondent 6). Evidence of other user's excreta was also a *disliked* aspect recorded during the user experience testing in Objective Four, Campus Respondent 01 noted "The smell was intense because someone had just used it. Despite the fact that the bowl was very clear and nice, the edge around it was dirty (covered with urine and hair)". Six other frustrations at evidence of other users were reported during the testing of the RWF indicating an aspect to be improved in future developments.

Sugden (2014) has written extensively on the subject towards sanitation behaviour. Based on Sugden's 20-year experience in the sanitation sector in Asia and Africa. Sugden (2014), states that a latrine will never be seen as aspirational if there is any sight or smell of faeces. He further elaborates that the features of an aspirational latrine be it, on the slopes of the Himalayas will or the depths of the Rift Valley will be remarkably similar. As Sugden's statement is based on visceral human nature, it could be inferred that the aspects that cause a bad toilet experience could cross economic boundaries as well as continental. Although excreta can also be referred to as 'human waste', treated correctly this can be used as a resource. The organisations *'SOIL'* and *'X-runner'* collect excreta from households in urban environments to convert to compost for use on crops (Rao *et al.,* 2016). Similarly, the Eco-community from Objective Four see the benefit of transforming their excreta into compost crop growth. The process of converting excreta into compost was the reason for the majority of the pleasing aspects answered in relation to using the UDDT by the group with such answers as “Understanding use of urine and faeces as compost/resource” (eco-community Respondent 09). Findings of this research imply that repulsion to stimulus from excreta is instinctive but far too few people see the potential benefit to be had from resource recapture. The flush and forget mentality and dilution with large amounts of water prevent it from being an option to many.

Key theme B: The perception that the flushing toilet is best is universal but has to change

Of the 78 interviews that took place in Kumasi, Ghana, only four respondents had flushing toilets. One of these four (Ghanaian Respondent 77) declared “it makes me more special” when referring to her flushing toilet. An elderly gentleman (Ghanaian Respondent 27) said he didn’t mind walking to the public toilet because it the toilet is flushing and he “likes modern toilets”. The aspiration to own a flushing toilet is widespread. The world’s ever increasing population aspire to own a flushing toilet but the environmental ramifications of more flushing toilet users would be ecologically devastating (Narain, 2002; Sugden, 2014). It is estimated that the number of people living in severely water stressed environments will increase from 1.7 billion in 2003, to 2.7 billion in 2050 and 5 billion people could be living under at least moderately stressed conditions (Oki, 2003) (Schlosser et al., 2014). Flushing toilets provide the desirable ‘flush and forget’ experience with no evidence of other people’s excreta but require a large volume of water to do so. Ideally, a mentality shift would take place in order for people to know longer aspire to own a flushing toilet and the convenience it provides but instead, value the water that they would be polluting. In the eco-community of Objective Four, the majority of the answers (18 out of 40) to what were the most pleasing aspects were in relation to the benefits of the process, for example “knowing not wasting water” (Eco-Community Respondent 11). The majority of the frustrating aspects (16 out of 41) were related to the user experience such as “sight of other people’s poo” (Eco-Community Respondent 03). This would suggest that to encourage more adopters to use UDDT the benefits that come from the process have to be promoted and user experience frustrations have to be addressed. As the eco-community have chosen to live an off-grid lifestyle, they will almost certainly be considerably more environmentally concerned than average members of the public. The ecotourism and adventure tourism sectors offer a potentially lucrative market to encourage investment that also services environmentally conscious users. New waterless toilet technology that meets the pleasant experience that wealthy travelers are used to, but is still in-line with traveler’s off-grid experience could provide a suitable secondary target market for new innovations (Buckley, 2009).

Changing the mentality of the average resident of a developed country will be difficult as Black and Fawcett (2008) describe; “*Aesthetics, convenience and pleasantness are unchallengeable winners in environments economically able to uphold the social and consumer status of the in-house bathroom and WC”.* It could be reasoned that the flushing toilet has changed so little in the past two centuries because it works well from the user’s perspective and the user doesn’t talk about its use because it’s an unpleasant subject. In Victor Papanek’s seminal book *‘Design for the Real World’* he explains that as the toilet is not a fashionable item, there is a lack of desire to upgrade. If toilets were to become something that consumers ‘traded in’ the industry would improve massively. One country that views toilets similarly to how Papanek describes, is Japan. Instead of being an object that is shut away, toilets are ‘must-have’ aspirational products (George, 2008). The perception of the toilet in Japan has shifted from a thing of convenience to something that is coveted and the demand has created a new market and new behaviour amongst users (Adhiutama, Shinozaki and Yoshikubo, 2009; Szczygiel, 2016; Tripsas, Egawa and Fukuyoshi, 2009). This suggests that a mentality shift causing new attitudes is possible within sanitation and the private act of using a toilet.

6.2.3 Objective Three: To develop and test a technology to improve the user experience of a waterless toilet.

The third objective began with the RWF as a concept and concluded with a functioning prototype. At the core of the design brief was to improve user experience and meet the requirements of the NMT. It is intended that this chapter could be used by other designers and innovators to inform procedure for developing improved sanitation.

Key theme A: Developing sanitation technology raises a number of challenges.

Developing technology for use in toilets will require additional considerations than normal development process at a number of stages along the innovation process. Researching such a personal topic is very challenging and has been noted as such by other researchers in particular the Anthropologist Van Der Geest (2007) in the publication 'not knowing about defecation'. Whilst attempting to gain an understanding current user behaviour of the primary target market of Kumasi, Ghana, in Objective Two, user demonstrations were employed as a part of the contextual interviews. Demonstrating how they cleaned the toilet was acceptable but demonstrating the act of defecation would not obviously not be acceptable due to privacy and ethics and could therefore not a true demonstration of use (Goffin, Lemke and Koners, 2010). To circumvent this, the researchers employed techniques such as asking the subjects to "pretend as if they were teaching a child" and having them demonstrate without disrobing. Testing of any new prototypes or technology with users such as in Objective Four can also not be observed and instead anonymous questionnaires were the most appropriate.

During the development and testing with real faeces that took place in Objectives Three and Four, special care has to be taken during collection, handling and disposal. Testing should be as realistic as possible in order to give the most accurate insights into performance and this will require the use of real faeces when practical. Simulant faeces will be suitable for many tests during the innovation path when developing sanitation technology. During the surface cleaning test in Objective Three, Soybean paste was decided on as being the most practical media to use. The testing required multiple tests over a number of days so consistency in formula was key. The Soybean paste was a commercially available product with consistent recipe and already used by the industry during research and development (George, 2008). The challenges of working with real faeces and simulant faeces can be found in Appendix D.

Key theme B: There isn't one toilet solution but attributes that are transferable.

Avellan (2017) succinctly describes the world's sanitation crisis in an online conversation piece as "the world needs more toilets – but not ones that flush". A toilet developed for a developing country may find a niche group of adopters in a developed country making it a reverse innovation. However, given the ubiquitous use of water in sanitation, a water-free toilet may pose a challenge in the form of user resistance to the wider population. It is likely that a range of technological innovations will be required to counteract such resistance, perhaps using different configurations in different localities, depending upon local cultural practices and expectations. Design features and attributes need to be developed to improve user experience but also have to take a number of factors into consideration for each specific target market. A pleasant user experience over a poor user experience is defined as *'relative advantage'* one of the five characteristics identified by Rogers (2010) as leading to adoption. Five particularities that are commonly associated with innovations for developing countries are: quality, affordability, accessibility, scalability and sustainability (Hadengue, De Marcellis-Warin and Warin, 2017). The research focussed on urban environments as the high populations and densely populated environments inflame issues with sanitation further. Figure 88 depicts the four main roles of water within a flushing toilet and will be used to discuss how technology can replace water.

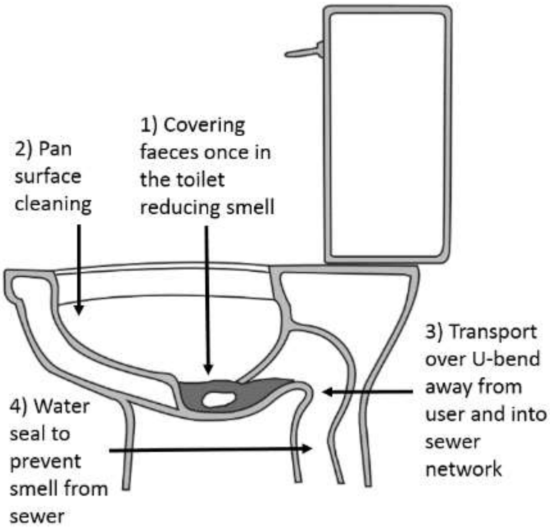


Figure 88 - Diagram of the various roles water has within a flushing toilet to provide a good user experience. (Tierney, R. 2017)

1) Odour reduction

The odour extraction of a Ventilated Improved Pit (VIP) Latrine is a simple yet effective at removing odour provided properly constructed and suitable for the toilet location (Practical Action, 2004). Ensuring that ventilation doesn’t allow the easy movement of insects to come in contact with the faeces is incredibly important to prevent the spread of disease into the community (Mecca, Davis and Davis, 2013b). An integrated odour ventilation system has been proposed using a small fan to drive the extraction (Seo and Seouk Park, 2013). This type of internal odour extraction would be recommended for the toilet in the case study, the NMT. Odour from the holding tank was transferred by the RWF during user simulation testing in Objective Four and was noted as a concern. More advanced methods of neutralising odour have been commercially implemented but testing during Objective Three and detailed in Appendix A.10 proved inconclusive due to testing failures. Low energy odour neutralising technology has potential provided it can be effective with low energy consumption. This will not only improve user experience but could also reduce flies being attracted to the excreta of a pit latrine and therefore reduce disease transfer. The chemical used in Clean Team toilets in Kumasi, Ghana, was the cause for a number of user frustrations. The strong smell required to mask the smell of faeces was overpowering to users with comments such as “smell of chemicals in the toilet frustrate her” (Ghanaian Respondent 12). Although the chemical will smell better than faeces, it seems just replacing one strong smell with another is not conducive to a good user experience. Preventing the user from smelling the odour from excreta or previous users is relatively straightforward as it has been proven to work on even the simplest of toilets (VIP latrines). An effective extraction method to provide the user with an odourless experience will be a valuable selling point in the adoption of waterless toilet technology.

2) *Surface cleaning*

Faecal fouling was identified in both the primary target market (“squatting people miss the target and defecate around it” Ghanaian Respondent 68) and secondary target market (“Faeces getting stuck to the side” Eco-Community Respondent 6) as being a frustration. Due to faeces viscoelastic nature and varied composition it is a very challenging substance to repel and prevent form adhering to a surface (Lentle and Janssen, 2011). Electrolysed water and ultraviolet lighting is used to ‘self-clean’ the pan of the latest high-tech toilet by TOTO that retails for approximately $9,000 (Belussi and Orsi, 2015). Simpler, low-cost methods that also do not use large quantities of water and improve the user experience, would be ideal. Repelling liquid with high surface tension such as urine is a relatively common material requirement and low surface energy materials such as PTFE or silicone can perform this task. A material with a lower surface energy could reduce the urine droplets reported by Campus Respondent 07 as a frustration during user testing of the RWF (“Urine droplets visible on pan from previous use”). Omniphobic surfaces are engineered to repel everything that could come in contact with it (Wang and Ondrey, 2016; Wong et al., 2011). A new Omniphobic surface called Slippery Liquid Infused Porous Surface (SLIPS) was demonstrated during Objective Three with real faeces against existing materials used currently in toilets. The surface performed very well completely repelling the faeces sample for the first few tests, suggesting there is a limit to performance. The properties that make faeces difficult to be repelled, force the boundaries of material science. A material that can meet the challenging surface properties required whilst being practical to make at large scale for relatively low cost, would likely be of value to other industries also. During Objective Four, testing with a secondary target market the RWF was demonstrated with sawdust as if the mechanism was being used as the interface of a composting system. The sawdust acted as a sacrificial layer similar to a sacrificial layer of paper used in incinerating toilets and the concept proposed by Lenau and Hesselberg (2015). This is also similar to the function of the lubricant used in SLIPS but on a much larger scale (*e.g.* instead of the substrate being separated from the faeces by less than a millimetre of lubricant, there is a few hundred millimetres of sawdust that the faeces lands on). Sawdust is required within composting to facilitate the process so using the material to prevent fouling is convenient. Additional materials (such as the lubricant of SLIPS) will not always be accessible for the user or compatible with the system. Preventing faecal fouling with inherent material properties and not using expensive technology, additional consumables or large volumes of water will ensure a more pleasant experience for the user compatible with a variety of systems.

3) Transport

Toilets such as Propelair reduce water use by 84% and transport the excreta into existing sewers with the assistance of air (Fane and Schlunke, 2008). The compatibility of the system with existing infrastructure as well as providing a good user experience and saving large amounts of water is a very good example of improved toilet systems the world needs (Jenssen et al., 2003). The long-term money saving benefits of these systems would also be highly desirable to people even if they are not environmentally conscious (Littlewood, Memon and Butler, 2007). Foam-flush toilets use a biodegradable soap that foams around the rim and covers the bowl after each use instead of using water. A small fan in a detergent produces the bubbles that provide comfort, cleaning and excreta conveyance commonly into a household composting unit (Anand and Apul, 2014). Foam flush would not be designed to improve UDDT toilets at the eco-community in Objective Four, as they rely on gravity for the excreta to drop into the wheeled bins below.

4) Sealing the user away from the excreta

Loowatt uses an innovative sealing method to effectively package the excreta of each user for safe storage until collection. There is no evidence of the previous user in the toilet but instead, a clean new surface (Siegel, 2015). The RWF was also designed to provide users with a clean bowl before each use and no sight of other user's excreta in the holding tank below. One of the members from the secondary target market noted one of their frustrations as being "Sight of other people poo" (Eco-Community Respondent 03) and they strongly believed the RWF could improve the frustration. Initial user testing conducted in Objective Four raised a concern from one user that there was a "slight odour when opening the lid" which would be caused by the "stink bomb" that the researchers conducted the simulation testing recorded. Sealing users away from excreta below could also reduce the association with disease that was observed during Objective Two in Kumasi, Ghana.

The first two functions of water in toilets mentioned above (1. Preventing odour and 2. Surface cleaning) are more obvious user experience features. The second two functions of water (3. Transporting waste and 4. Sealing the user from excreta) will be more case specific than the first two attributes and heavily influenced by how the excreta is processed. These features can be implemented in a variety of configurations depending on context.

6.2.4 Objective Four: To evaluate the new technology with real users and the potential for waterless sanitation technology to be adopted in a secondary target market.

The Objective covered the first trials of the user interface of the newly developed RWF. A major step towards a commercial product was having the real people use the toilet interface for the first time. A secondary target market was also identified and consumer insight was gathered by questionnaire and focus group discussion.

Key theme A: People without flush water toilets can be lead users in the design of improved toilets for everyone

Reverse innovation has been commonly associated with Von Hippel's lead-user theory (Hadengue, De Marcellis-Warin and Warin, 2017). Lead users are customers that have strong needs and are experts at using a product or service (Goffin, Lemke and Koners, 2010; von Hippel, 1986). An example of this is sports brands observing marathon runners to improve the next generation of running shoe for a recreational jogger (Son and Shu, 2012). Goffin et.al (2010) elaborates on this term further describing another subsection of this as being 'extreme users' who place extreme demands on their use of a product. In effect, designing products with the strict constraints of a developing country can push innovation to be entirely unlike an evolved existing solution and disrupt the market place.

When considering reverse innovation for sanitation, the primary target market of the NMT was people currently using un-improved toilets in Kumasi, Ghana. The RWF was designed to reduce odour from the stored excreta in the holding tank of the NMT without using any water, power or a change to user behaviour. The volume testing in Objective Three was conducted to ensure that the same standards expected of flushing toilet could also be obtained with the RWF and the material testing explored the idea of a surface repellent to faeces to improve user experience without the need for water. These strict requirements were extremely challenging but essential for a new technology to meet not only the needs of a toilet system but also the person who will use the toilet. This resulted in a technology that has potential to be transferable to a secondary target market such as an eco-community as it requires no additional resources and intends to improve the user experience. In the secondary target market tested in Objective Four, the waterless toilet technology designed for a community thousands of miles away was well received. Individual respondent answers showed they *'agreed'* that six of the frustrations they recorded with their current toilet could be improved by the RWF, and *'strongly agreed'* that five of the frustrations could be improved with the technology. The secondary target market also responded favourably when measuring the RWF in relation to Rogers' characteristics of adoption (2010).

One of the designers of the LFC describes the role of the designer in reverse innovation; "To successfully practice reverse innovation, designers must first understand the needs of stakeholders in the developing world. This insight will lead to the creation of high performance, low-cost, innovative solutions that address the most compelling development challenges that affect quality of life, as well as unlock massive markets of new consumers in emerging economies". Existing sanitation companies or innovators wanting to exploit the need for innovation within sanitation should follow this advice from a creator of a disruptive and successful product at different economic levels.

6.3 Assessing reverse innovation for improving urban sanitation

Govindarajan & Ramamurti (2011) defines 'reverse innovation' as "the case where an innovation is adopted first in poor (emerging) economies before 'trickling up' to rich countries". Von Zedtwitz et.al (2014) expands on the term to identify 16 variations of innovation flow depending on whether the different phases take place in a developing or a developed country. These phases include the concept ideation, product development, primary target market introduction, and, which subsequent secondary market introduction. Of the 16 variations, 10 are reverse innovation flows which are then differentiated into strong and weak reverse innovation (von Zedtwitz et al., 2015).

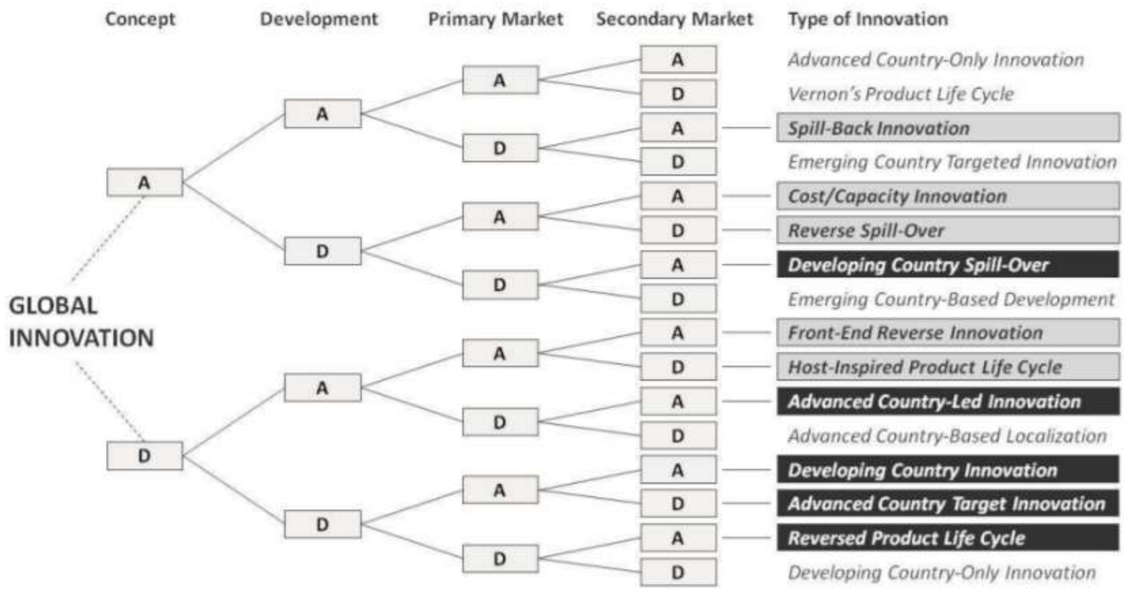


Figure 89 - Map of global innovation flows. Grey-shaded innovations are reverse innovations in a weak sense, black-shaded innovations are reverse innovations in a strong sense, and no shading is not a reverse innovation (von Zedtwitz et al., 2015).

By considering existing technologies profiled in Objective One and assessing the innovation path of each with von Zedtwitz (2015) typology, Loowatt is the only example of reverse innovation in a weak sense. Figure 90 depicts the innovation path as an example for how von Zedtwitz typology diagram is used.

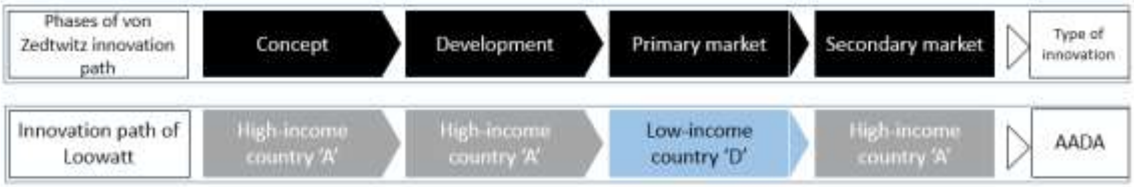


Figure 90 - Loowatt innovation path for inclusion into von Zedtwitz *et al*. typology of reverse innovation (2015)

- **Loowatt;** AADA- Spill-back Innovation –Weak sense of reverse innovation
- **Clean Team;** AADD- Emerging country targeted innovation – Nonreverse innovation
- **Sato pan;** AADD- Emerging country targeted innovation – Nonreverse innovation
- **Peepoo bag;** AADD- Emerging country targeted innovation – Nonreverse innovation
- **Ventilated Improved Pit (VIP) Latrine;** DDDD- Developing country only innovation[26]
- **Otji toilet pan;** DDDD- Developing country only innovation

Loowatt is an example of a 'Spill-back Innovation' which is reverse innovation in a weak sense. The sealing toilet concept was originally designed in the UK by Virginia Gardner as part of a Masters Degree project and further developed in the UK (Larsson and Nilsson, 2013). The primary target market is in Antananarivo, Madagascar where they currently have approximately 100 household toilets. The secondary target market is for UK festivals where they luxury eco toilets (Loowatt, 2017b; Purves and Gardiner, 2013).The company's business model is adaptable to different scenarios that require off-grid sanitation (Siegel, 2015). They have a

[26] The 'improved' part of the VIP latrine is attributed to Peter Morgan in 1973 who worked for the Ministry of Health in Rhodesia (Black and Fawcett, 2008)

product platform that is transferable to different target markets as the user experience is at the core of their offering. Loowatt have improved the lives for people currently using unimproved sanitation in developing communities and in a developed country they have improved the user experience of a niche secondary target market. The RWF could also improve the lives of people using unimproved toilets but also provide a more pleasant experience to users of composting toilets for one example. Hypothetically, if commercially successful in both the primary target market and a secondary target market in a developed country, the RWF would also be classed as 'Spill-back innovation'. Strong-sense reverse innovation has not been observed in sanitation yet.

There are challenges and risks to reverse innovation within sanitation which are not always discussed. As Hadengue (2017) states; "reverse innovation is not easy to achieve", the author continues to summarise that the focus in literature tends to be on the successful cases. Risks that all multinational corporations have to consider when pursuing reverse innovation include; brand cannibalisation, risk of technology leaks, and a drain human resource (Furue and Washida, 2014). Harris *et al.* (2015) investigated perceived barriers to Reverse Innovation within healthcare solutions and concluded that prior assumptions about the quality of innovations from developing countries were barriers. Toilets in developing countries can have a notorious reputation for being unpleasant to use. The idea that technology developed for use in such a location would not necessarily be appealing. For example; if a new toilet for mobile homes or caravans used technology developed for aeroplanes, it would probably give a better impression than a toilet that uses technology developed for developing countries.

Reverse innovation is generally acknowledged as a strategy that can be implemented by organisations of various sizes (Hadengue, De Marcellis-Warin and Warin, 2017). An example of a multination toilet corporation who are potentially fostering reverse innovation is Roca. Roca are one of the world's largest toilet manufacturers, primarily the producers of advanced country-only innovation. This could begin to change however. In 2014 they opened the Roca Design Centre Asia in Foshan China, their first design centre in a developing country to adapt European collections to the Asian market as well as designing specific products for the Asian market (Roca, 2016). Building a Local Growth Team (LGT) in an emerging region is in-line with what Govindarajan's calls the 'reverse innovation mind set'. Importantly, Roca specifically declare the design centre will develop 'Asian-specific' products and not just 'Asian-adapted' which would be classed as Glocalization (Govindarajan, 2012). A range of issues have to be considered in this relationship in order to better facilitate and promote reverse innovation. These include the autonomy and control given to the LGT, the resources the LGT have access to and the analysis of the gap between the developing region and the industrialised region (Govindarajan and Trimble, 2013). The main benefits of the LGT are their strong instinctive understanding of local customer needs and connections to local actors, including financial institutions and governments. The implementation of local growth teams in India was a critical step for General Electric (GE) to not only increase growth in the region but to also develop products that were successful examples of reverse innovation (Hadengue, De Marcellis-Warin and Warin, 2017). A new product developed in this manner that is successful in a developed country would be categorised as Inductive Reverse Innovation (IRI) as the product was intended to transfer from the LGT. Whereas Loowatt for example, would be classified as Coincidental Reverse Innovation (CRI) as the original innovation was not intended to find a secondary target market (Furue and Washida, 2014).

The approach that each designer, innovator or company has to implementing reverse innovation to improve sanitation will vary greatly. As this is still an emerging field of research there is still a lot of uncertainty with best practice and reducing risk (Hadengue, De Marcellis-Warin and Warin, 2017).

6.4 Future opportunities

The recommendations for future work will now be presented in three sections for industry, design innovators and researchers:

Opportunities for the sanitation industry: Toilet manufacturers following Govindarajan's steps for encouraging reverse innovation could be a lucrative approach for the manufacturers and a benefit to consumers at both ends of the economic pyramid. This could also disrupt the sanitation industry. Developing new toilet technology using the parallel innovation model proposed by Judge et al (2015), utilising a transferable product platform to lower costs and improve performance. The 2.3 billion people who lack access to sanitation are a huge untapped market in need of innovation by manufacturers. As the combined buying power of the four billion people living in the BoP is $5 trillion (Karamchandani, Kubzansky and Lalwani, 2011) there can be reward for the risk taken. Toilet manufacturers should also reduce the amount of water used by flushing toilets.

Opportunities for design innovators: More research and development into improving user experience for toilets utilising Human Centred Design. More self-contained toilet services will improve millions of people's lives and are already proven to be effective in other parts of the world. New low-cost, reliable methods of preventing odour could improve millions of the most basic toilets in the poorest parts of the world.

Opportunities for future research: Behaviour change methods such as CLTS are incredibly important and should be promoted as much as possible. Shifting the perception that flushing toilets are the best would be an appropriate use of these types of methods.

6.5 Chapter Six highlights:

This chapter identified key themes from each of the objectives and took a holistic approach to analyse and discuss each of the themes. Evidence from across the whole thesis was synthesised for each theme in order to answer the move towards answering the research question.

“Sanitation is more important than political independence”

Mahatma Ghandi

7 CONCLUSION

This chapter will answer the research question from the start of the thesis that posed: ***'How can reverse innovation improve progression up the sanitation ladder?'*** This will be the major contribution of the thesis. Additional contributions will be presented to demonstrate how this research has already benefited academia, industry and the NMT project. With limitation of the research and personal journey to close the research.

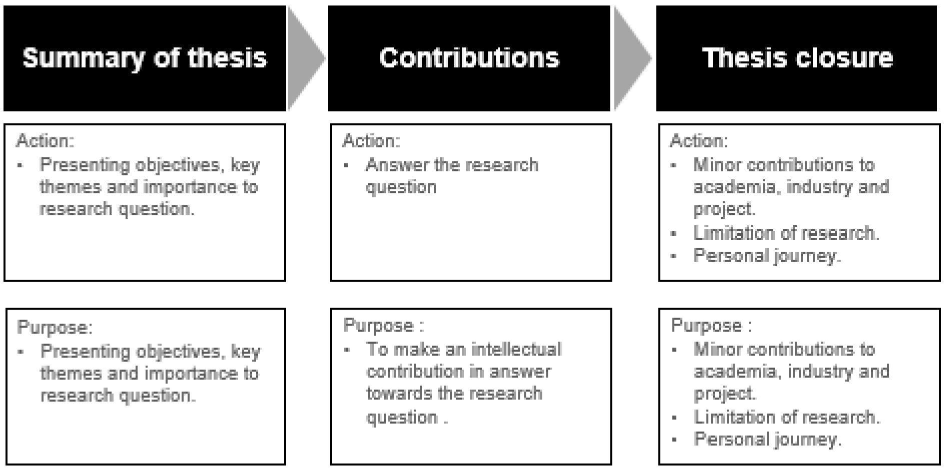


Figure 91 – Structure of conclusion chapter and rationale

7.1 Contribution of knowledge

At the bottom of the economic pyramid, 2.3 billion people lack access to basic sanitation, meaning they either practise open defecation, use unsafe toilets, or facilities shared with other households. This leads to a myriad of issues such as an unpleasant user experience, the risk of assault, and the spread of potentially deadly diseases. In urban environments, poor infrastructure and dense populations intensify these problems. At the top of the economic pyramid, 2.9

billion people have a toilet that safely removes excreta, but does so using an average of nine litres of water per visit. From the user's perspective the system is very convenient, as the push of a handle removes unpleasant waste. This convenient eradication of what, for many, is an embarrassing act is one reason why its technology has changed little over the past 200 years. To provide this expedient 'flush and forget' experience, 15,000 litres of water are used per person per year. This is an unsustainable amount considering that water resources are likely to become much more strained as the global population is expected to reach 9.7 billion in 2050. Excreta has valuable reuse potential, but – instead of being utilised in a beneficial way – is diluted with huge amounts of clean water, which itself has to be treated in order to avoid polluting the environment further. Water-flushing toilets are ubiquitous in the developed world, and also constitute what the rest of the world aspire to own. As 2.5 billion people will be added to the world's urban populations by 2050, with close to 90 percent of the increase concentrated in Asia and Africa, issues surrounding sanitation will only be exacerbated further.

The user experience and toilet interface is a crucial but often overlooked aspect of the global sanitation crisis. When user experience is improved, the likelihood of adoption of new low-water technology will be increased. There is no one-size-fits-all solution, but features and attributes that are transferable across the sanitation ladder do exist. Improving the user experience within strict constraints could result in innovations that have the potential to transfer to markets in developed countries – something that might be defined as reverse innovation.

Reverse innovation has the potential to improve the lives of millions, and also to reduce the environmental impact of water flushing toilets. It is also a proven strategy from a commercial perspective. The medical profession, for example, has already benefitted greatly from reverse innovation with improved wheelchairs and portable ultrasound scanners. Multinational corporations such as GE and Harman have invested – both financially and in other ways – to gain a competitive edge, as well as protecting their position from emerging competitors. Toilet manufacturers or design innovators that target the 2.3 billion without basic sanitation have an incredible opportunity, as so much innovation is required in this area. Gaining a deep understanding of the frustrations, needs and aspirations of people is integral to ensuring delivery of a product that is wanted as well as needed. The repulsion caused by excreta is a visceral inherited response and is therefore universal. Toilet technology that can remove excreta with as little power or water as possible will be very desirable, and hence more transferable to other target markets. The strict constraints of a product for the bottom of the pyramid can force designers to push the boundaries of innovation and unlock disruptive, technologically radical concepts that might have universal appeal. For example, omniphobic surfaces could improve pit latrines not just in slums in the developing world, but also enhance user experience of low-water-flushing toilets in the developed world. Another example could be the Rotating Waterless Flush, which not only reduces the frustrations with a toilet-collection service such as Clean Team, but also enhances user experience of a compost toilet at an eco-tourism site.

Reverse innovation is thus perfectly suited to improve global sanitation as there is a desperate need for innovation at the bottom of the pyramid … and a stagnated market at the top that needs to reduce water usage. The potential benefits of reverse innovation in sanitation include: a reduction in environmental degradation; the creation of new markets for existing toilet manufacturers; and improved toilet facilities for the billions of people who desperately need them.

Using a toilet is a basic human act. The ubiquitous provision of safe and eco-friendly sanitation is therefore essential if we are to improve the safety, the health, the dignity and the well-being of people across the world. The benefits of achieving this aim are not just limited to questions of basic health and safety – they encompass wider socio-economic issues such as education, the realisation of human potential, and a nation’s economic growth. Put simply, access to high-quality sanitation is a prerequisite for the full and productive enjoyment of human life and human rights everywhere. It is more even than just what the world needs, and what natural justice demands: it is the environmental and moral imperative of the present day.

7.1.1 Evidence for contribution

This has been formed from evidences collated throughout the thesis. Table 23 declares how each objective has produced key themes pertinent to answering the research questions.

Table 23 - Key themes of thesis

Objective	Key theme	Importance to research question
Objective One: To review literature surrounding low-water sanitation options with a focus on the user experience.	*The approach to monitoring and improving global sanitation has to be improved*	New toilet technology should address the higher levels of Kvarnström's (2011) sanitation ladder and incorporate Jenkins & Sugden (2006) drivers for adoption.
	There is a need for improvements to toilets across whole sanitation ladder.	Designing new resource constrained toilet technology for the poorest people in the world can produce an innovation that will meet the needs of a niche group or lower water usage in the developed world.
Objective Two: To use ethnographic research techniques to identify the frustrations and perceptions associated with using different toilets by residents in Kumasi, Ghana (the project's primary target market).	*Repulsion to excreta is human instinct but nuanced.*	Disgust will cause an almost universal negative user experience. Removing evidence of a previous user without water is challenging but it will likely create a positive user experience that will improve the likelihood of adoption.
	The perception that the flushing toilet is best is universal but has to change	There has to be a demand for low water or waterless toilets. Currently convenience and pleasantness of flushing toilets are barriers to adoption.
Objective Three: To develop and prototype a technology to improve the user	*Developing sanitation technology raises a number of challenges.*	New technology is needed in the sanitation sector but developing this type of technology raises a number of challenges unlike most

experience of a waterless toilets		other product development projects.
	There isn't one toilet solution but attributes that are transferable.	New technology has to meet the needs of the target market but there is potential for there to be benefit to a secondary target market. The likelihood of transferability is increased if the technology addresses frustrations that are basic human instinct and do not use additional resources.
Objective Four: To test and evaluate the technology with real users and the potential for the technology to be adopted in a secondary target market.	*People without flush water toilets can be lead users in the design of improved toilets for everyone*	Technology designed for developing country was positively viewed by secondary target market.

7.2 Additional contributions

This research has implications for designers, policy makers, sanitation businesses, NGO's and educators wishing to develop the skills of those who will be working on this issue. This section will now specify the individual contributions that have resulted from this research.

Academic contributions

This research identified the potential for reverse innovation to address issues with global sanitation by improving toilet access at the bottom of the economic pyramid and reducing water use at the top of the economic pyramid. The importance of user experience within sanitation was highlighted as a key method for this to be successful.

The work has been presented at The World Water Congress 2017 in Cancun Mexico and to the Innovation Research Group at Imperial University. The author will be returning to Imperial University to present this research to the Masters for Global Public Health as part of the Global Innovation module in 2018. One article is under review with the author of this thesis listed as a co-author and one paper is ready for submission with the author listed as lead author.

Project contributions

This research has led to a deeper understanding of toilet technology and behaviour in the target market and identified the potential for a secondary target market. The development and testing of rotating bow and swipe blade have informed and improved the RWF. Collaboration instigated with Pennsylvania State University to develop new materials for use within waterless toilets. The understanding of target group expectations and technology have informed the testing currently underway in an undisclosed location in Africa.

Industry contributions

This research has stressed the importance of user-centred design within sanitation, encouraging the inclusion of the user experience into future action by NGO’s and policy makers. The author has presented at World Toilet Day at the Roca Gallery in Barcelona on the importance of user experience and the need for improved sanitation for the world’s poorest communities. The potential that omniphobic surfaces have for this application have also been tested for the first time. The Rotating Waterless Flush has also been patented (WO 2017/149036 A1) and is currently taking part in extended user trials in an undisclosed location in Africa.

7.3 Limitations

As the Nano Membrane Toilet was a live project, there was always a balance between research and project commitments which has been a pleasure and a challenge. Due to the confidential nature of the project and high profile status (*i.e*. The Bill and Melinda Gates Foundation funded project) the testing needed to adhere to the requirements of the project as well as the research. The ideal conclusion for this research would be long term testing of the RWF with a secondary target market or deeper investigation into transferring different toilet technologies to a secondary target market. This was not possible due to time constraints and project demands. Developing the WRF from basic concept to being tested with real users had to be a main focus in order to meet project timeline and sponsor goals. Acquiring ethical approval for testing was a valuable learning experience but time consuming; this has enlightened the author on rigour, good practice and health and safety considerations when working on such a project. This should not be underestimated by future innovators in this areas.

7.4 Personal journey and learnings

'The Reinvent the Toilet Challenge' has been an incredible experience over almost five years and I feel privileged to have been a part of it. I know the challenge will improve the lives of millions of people and I hope that the Nano Membrane Toilet will go on to help as well. I also hope that more people will try to develop new environmentally conscious sanitation solutions to improve health and dignity especially in low income countries. I have seen first-hand the importance of resolving issues surrounding sanitation and would love to continue trying to improve them.

Figure 92 - The Author in Kumasi, Ghana (photo courtesy of J. Larsson (2015)

Figure 93 - The Nano Membrane Toilet user interface in an undisclosed location in Africa ready for the next set of user testing as the project continues. (Image courtesy of Jan Henning, 2017)

3M (2015) *Innovations in Bonding to Low Surface Energy Surfaces*. Available at: http://multimedia.3m.com/mws/media/755526O/innovations-in-bonding-to-low-surface-energy-white-paper.pdf (Accessed: 5 October 2017).

Adhiutama, A. et al. (2009) 'Innovation Toilet and Barriers of Diffusion in Developing Country Case Study: TOTO Electronic Bidet Seat Toilet', *The Asian Journal of Technology Management*, 2(2), pp. 88–97.

Afful, K. et al. (2015) '*Assessing public perception of odours in a community: case of Ayigya Zongo, an urban poor community in Ghana*' Available at: http://www.iwaponline.com/washdev/up/washdev2015104.htm (Accessed: 22 June 2015).

Anand, C.K. and Apul, D.S. (2014) 'Composting toilets as a sustainable alternative to urban sanitation – A review', *Waste Management*, 34(2), pp. 329–343.

Anon (2009) '*JAMII BORA TRUST IMPACT ASSESSMENT REPORT 0N THE PEEPOO BAG, SILANGA VILLAGE, KIBERA, NAIROBI-KENYA*' Available at: https://www.ircwash.org/sites/default/files/Ondieki-2009-Impact.pdf (Accessed: 26 May 2017).

Antoniou, G. et al. (2015) 'Evolution of Toilets Worldwide Through the Millennia', *Sustainability* Available at: 10.3390/su50x000x (Accessed: 6 July 2016).

Arku, F.S. et al. (2013) 'Toilet is not a dirty word: close to meeting the MDGs for sanitation?', *Taylor & Francis Development in Practice*, 23(2), pp. 184–195. Available at: 10.1080/09614524.2013.772121 (Accessed: 19 November 2017).

Arocha, J.S. and McCann, M.J. (2013) 'Behavioral economics and the design of a dual-flush toilet', *American Water Works Association*

Asghar, R. (2014) Why Silicon Valley's 'Fail Fast' Mantra Is Just Hype, *Forbes*, Available at: https://www.forbes.com/sites/robasghar/2014/07/14/why-silicon-valleys-fail-fast-mantra-is-just-hype/#38a5874f24bc (Accessed: 1

October 2017).

Ashby, M.F. and Johnson, K. (2013) *Materials and Design: The Art and Science of Material Selection in Product Design*. Butterworth-Heinemann. Available at: https://books.google.com/books?id=lyDEACMTtUEC&pgis=1 (Accessed: 4 August 2015).

Auerbach, D. (2016) *Sustainable Sanitation Provision in Urban Slums – The Sanergy Case Study*. Cham: Springer International Publishing. Available at: 10.1007/978-3-319-28643-3_14 (Accessed: 20 November 2017).

B-N Sanders, E. and Jan Stappers, P. (2008) ‘Co-creation and the new landscapes of design’, *Co-Design* Available at: 10.1080/15710880701875068 (Accessed: 23 May 2018).

Balu, B. et al. (2008) ‘*Fabrication of " Roll-off " and " Sticky " Superhydrophobic Cellulose Surfaces via Plasma Processing*’ Available at: 10.1021/la703766c (Accessed: 4 September 2017).

Banerjee, A. et al. (2013) ‘A STUDY OF OPEN AIR DEFECATION PRACTICE IN RURAL NANDIVARGAM VILLAGE’, *International Journal of Bioassays* Available at: file:///C:/Users/s203465/Downloads/237-233-2-PB.pdf (Accessed: 20 November 2017).

Bartram, J. et al. (2010) ‘Hygiene, sanitation, and water: forgotten foundations of health.’, *PLoS medicine*, 7(11) IWA Publishing, p. e1000367. Available at: 10.1371/journal.pmed.1000367 (Accessed: 18 July 2016).

Belussi, F. and Orsi, L. (2015) *Innovation, alliances, and networks in high-tech environments*. Available at: https://books.google.co.uk/books?hl=en&lr=&id=U_OPCgAAQBAJ&oi=fnd&pg=PA245&dq=ewater+toto+toilet&ots=THkg0wWRe7&sig=DE0WtRFvspwrOveOCwgLIdT-Wsc#v=snippet&q=ewater&f=false (Accessed: 16 October 2017).

Beylerian, G.M. et al. (2007) *Ultra materials : how materials innovation is changing the world*. Thames & Hudson.

Bhushan, B. et al. (2009) ‘Self-Cleaning Efficiency of Artificial

Superhydrophobic Surfaces', *Langmuir*, 25(5) American Chemical Society, pp. 3240–3248. Available at: 10.1021/la803860d (Accessed: 3 October 2017).

Bhushan, B. et al. (2010) 'Lotus Effect: Surfaces with Roughness-Induced Superhydrophobicity, Self-Cleaning, and Low Adhesion', in *Springer Handbook of Nanotechnology*. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 1437–1524. Available at: 10.1007/978-3-642-02525-9_42 (Accessed: 3 October 2017).

Black, M. and Fawcett, B. (2008) *The Last Taboo: Opening the Door on the Global Sanitation Crisis - Maggie Black, Ben Fawcett - Google Books*. Available at: https://books.google.co.uk/books?id=TV0YWguY3nEC&pg=PT247&lpg=PT247&dq=van+der+geest+sanitation+kumasi&source=bl&ots=M-WtPGmQor&sig=iMfDE2KCOxfZIQLLcpjBHOuUVhc&hl=en&sa=X&ved=0ahUKEwj589-ZjvHRAhWsLMAKHcm4AiEQ6AEIOTAH#v=onepage&q=van der geest sanita (Accessed: 2 February 2017).

Brace, I. (2008) *Questionnaire design : how to plan, structure and write survey material for effective market research*. Kogan Page. Available at: https://books.google.co.uk/books/about/Questionnaire_Design.html?id=0r8xOI5rBZoC&redir_esc=y (Accessed: 26 November 2017).

Braun, R.J. et al. (2003) 'Modelling drainage of the precorneal tear film after a blink.', *Mathematical medicine and biology : a journal of the IMA*, 20(1) IWA Publishing, pp. 1–28. Available at: 10.2166/washdev.2015.178 (Accessed: 25 July 2016).

Bristow, G. et al. (2004) 'WATERLESS URINALS: FEATURES, BENEFITS, AND APPLICATIONS', *Journal of Green Building* Available at: http://oaktrust.library.tamu.edu/bitstream/handle/1969.1/4626/ESL-HH-04-05-26.pdf (Accessed: 5 September 2017).

Britannica (2017) *Nepenthes | plant genus | Britannica.com*. Available at: https://www.britannica.com/plant/Nepenthes (Accessed: 10 November 2017).

Buckley, R. (2009) *Ecotourism : principles and practices*. CABI.

Available at: https://books.google.co.uk/books?id=qRzHNJgEiBEC&pg=PA131&lpg=PA131&dq=ecotourism+toilet&source=bl&ots=vizcgMDOCO&sig=jTIs0M6Ez1OAPPR2yI-qOrheoeA&hl=en&sa=X&ved=0ahUKEwjYhbP3kILYAhXCJ8AKHVPjATgQ6AEIUDAK#v=onepage&q=ecotourism toilet&f=false (Accessed: 11 December 2017).

Burge, S. (2011) *the systems engineering tool box*. Available at: https://www.burgehugheswalsh.co.uk/Uploaded/1/Documents/Functional-Modelling-Tool-Draft.pdf (Accessed: 8 November 2017).

Callow, M.E. and Fletcher, R.L. (1994) 'The Influence of Low Surface Energy Materials on Bioadhesion a Review', *International Biodeterioration & Biodegradation*, , pp. 333–348. Available at: https://ac.els-cdn.com/0964830594900922/1-s2.0-0964830594900922-main.pdf?_tid=4a803d8e-b41c-11e7-aaa6-00000aacb35f&acdnat=1508342106_5d516229aef4a6a51e360b5d9c43d627 (Accessed: 18 October 2017).

Callow, P. (2012) 'Building a Better Toilet', *The Journal of Global Health Care Systems*, 2(1)

Callow and Patricia (2012) 'Building a Better Toilet', *The Journal of Global Health Care Systems*, 2(1)

Carter, C.B. and Norton, M.G. (2013) *Ceramic materials : science and engineering*. Springer. Available at: https://books.google.co.uk/books?id=WRg_AAAAQBAJ&pg=PA232&lpg=PA232&dq=surface+energy+ceramic&source=bl&ots=7-vbX9fqeU&sig=MIktUq3KKOGBIw28TcqzIW8r5r4&hl=en&sa=X&ved=0ahUKEwi93NyG4azXAhXHI-wKHdeXBDwQ6AEIRTAE#v=onepage&q=surface energy ceramic&f=false (Accessed: 7 November 2017).

Chappuis, C.J.-F. et al. (2016) 'Sensory survey of key compounds of toilet malodour in Switzerland, India and Africa', *Flavour and Fragrance Journal*, 31(1), pp. 95–100. Available at: 10.1002/ffj.3293 (Accessed: 16 August 2017).

Chatterton, K. (2014) *A Collection of Contemporary Toilet Designs*. Available at: http://www.bluediversiontoilet.com/uploads/2/4/7/3/24735693/conte mporary_toilet_designs.pdf (Accessed: 3 September 2017).

Coffey, D. et al. (2014) '*Revealed preference for open defecation: Evidence from a new survey in rural north India*'

Coombes, Y. (2016) 'User-centred latrine guidelines – integrating CLTS with sanitation marketing: a case study from Kenya to promote informed choice', *SUSTAINABLE SANITATION FOR ALL* Available at: 10.3362/9781780449272 (Accessed: 26 November 2017).

Cooper, R. et al. (2002) '*Optimizing the Stage-Gate ® Process: What Best Practice Companies are Doing (Part One) Optimizing the Stage-Gate Process: What Best Practice Companies Are Doing – Part One*', 45(5) Available at: http://www.stage-gate.net/downloads/wp/wp_14.pdf (Accessed: 9 August 2017).

Cooper, R.G. (2008) 'Perspective: The Stage-Gate. Idea-to-Launch Process—Update, What's New, and NexGen Systems', *Journal of Product Innovation Management*, 25(3) Blackwell Publishing Inc, pp. 213–232. Available at: 10.1111/j.1540-5885.2008.00296.x (Accessed: 25 September 2017).

Cooper, R.G. and Edgett, S.J. (2005) *Lean, rapid, and profitable new product development*. Available at: 10.1111/j.1540-5885.2008.00296.x (Accessed: 14 November 2017).

Crossan, M.M. and Apaydin, M. (2010) 'A Multi-Dimensional Framework of Organizational Innovation: A Systematic Review of the Literature', *Journal of Management Studies*, 47(6) Blackwell Publishing Ltd, pp. 1154–1191. Available at: 10.1111/j.1467-6486.2009.00880.x (Accessed: 9 November 2017).

Cruddas, P. et al. (2015) 'User perspectives to direct water reuse from the Nano Membrane toilet', *38th WEDC International Conference, Loughborough University*. Available at: http://wedc.lboro.ac.uk/resources/conference/38/Cruddas-2251.pdf (Accessed: 6 September 2017).

Curtis, V. (2016) *Sustainable Sanitation for All*. Available at: 10.3362/9781780449272 (Accessed: 8 November 2017).

Danielsson, S. (2012) *Simple Handwashing Devices | SSWM.*, *Sustainable Sanitation and Water Mangement* Available at: https://www.sswm.info/category/implementation-tools/water-use/hardware/optimisation-water-use-home/simple-hand-washing-dev (Accessed: 12 December 2017).

Datta, A. and Mukherjee, S. (2016) *Structural and morphological evolution in metal-organic films and multilayers*. Available at: https://books.google.co.uk/books?id=sdeYCgAAQBAJ&pg=PA18&lpg=PA18&dq=Adhesive+forces+between+a+liquid+and+solid+cause+a+liquid+drop+to+spread+across+the+surface.+Cohesive+forces+within+the+liquid+cause+the+drop+to+ball+up+and+avoid+contact+with+the+surfac (Accessed: 5 September 2017).

David, L.T. (2014) '*A Case for Public Sanitation with On-Site Treatment in Ghana A Case for Public Sanitation with On-Site Treatment in Ghana in Partial Fulfillment of the requirements for the Degree of Master in City Planning*' Available at: http://web.mit.edu/watsan/Docs/Student Theses/Ghana/2014/Thesis_LaKisha_David_5-24-14.pdf (Accessed: 20 November 2017).

Dellström Rosenquist, L.E. (2005) 'A psychosocial analysis of the human-sanitation nexus', *Journal of Environmental Psychology*, 25(3), pp. 335–346.

Denyer, D. and Tranfield, D. (2009) 'Produing a Sytematic Review', *Sage hanbook of organizational research methods* Available at: https://www.cebma.org/wp-content/uploads/Denyer-Tranfield-Producing-a-Systematic-Review.pdf (Accessed: 15 December 2017).

Devine, J. (2010) '*Beyond tippy-taps: The role of enabling products in scaling up and sustaining handwashing*', 29(4) Available at: 10.3362/1756-3488.2010.033 (Accessed: 27 November 2017).

Dixon, A. et al. (1999) 'Water saving potential of domestic water reuse systems using greywater and rainwater in combination', *Water Science and Technology*, 39(5) No longer published by Elsevier, pp. 25–32. Available at: 10.1016/S0273-1223(99)00083-9 (Accessed: 20 November 2017).

Dreibelbis, R. et al. (2013) 'The Integrated Behavioural Model for Water, Sanitation, and Hygiene: a systematic review of behavioural models and a framework for designing and evaluating behaviour change interventions in infrastructure-restricted settings.', *BMC public health*, 13(1), p. 1015. Available at: 10.1186/1471-2458-13-1015

(Accessed: 11 July 2015).

duPont (2012) *DuPont TM Krytox ® Performance Lubricants Typical Properties of Krytox ® General-Purpose Oils and Greases*. Available at: http://www2.dupont.com/Lubricants/en_US/assets/downloads/H-58510-5_Krytox_Typical_Properties.pdf (Accessed: 5 October 2017).

Dzwairo, B. et al. (2006) '*Assessment of the impacts of pit latrines on groundwater quality in rural areas: A case study from Marondera district, Zimbabwe*' Available at: 10.1016/j.pce.2006.08.031 (Accessed: 20 November 2017).

Elledge, M.F. and Mcclatchey, M. (2013) '*India, Urban Sanitation, and the Toilet Challenge*' Available at: 10.3768/rtipress.2013.rb.0006.1309 (Accessed: 25 November 2017).

Esrey, S.A. (2001) 'Towards a recycling society: ecological sanitation – closing the loop to food security', *Water Science and Technology* Available at: http://wst.iwaponline.com/content/ppiwawst/43/4/177.full.pdf (Accessed: 15 November 2017).

Esrey, S. et al. (2001) *CLOSING THE LOOP Ecological sanitation for food security*. Available at: http://www.ecosanres.org/pdf_files/closing-the-loop.pdf (Accessed: 13 May 2016).

Exenberger, A. and Hamilton, C. (2009) *Facing tragedies*. Lit. Available at: https://books.google.co.uk/books?hl=en&lr=&id=Ik-PJM139G0C&oi=fnd&pg=PA163&dq=One+death+is+a+tragedy.+One+million+deaths+is+a+statistic&ots=EG7ddAdNjb&sig=PaoYXdkWKNejvbkLT5QVziGK4SA#v=onepage&q=One death is a tragedy. One million deaths is a statistic&f= (Accessed: 7 December 2017).

Exley, J.L.R. et al. (2015) 'The Sanitation Ladder, What Constitutes an Improved Form of Sanitation?', *Environmental Science & Technology*, 49(2), pp. 1086–1094. Available at: 10.1021/es503945x (Accessed: 20 November 2017).

Fane, S. and Schlunke, A. (2008) '*Opportunities for more efficient toilets in Australia – How low can we go? Opportunities for more efficient toilets in Australia - How low can we go?*' Available at: http://cfsites1.uts.edu.au/find/isf/publications/fane2008efficienttoilets.

pdf (Accessed: 7 September 2017).

Fawcett, B. (2009) ‘Making more than mention of an unmentionable crisis’, *Water & Wastewater International*, 24 Available at: file:///C:/Users/s203465/Downloads/out (3).pdf (Accessed: 14 December 2017).

Forbes, P. (2008) ‘Self-Cleaning Materials: Lotus Leaf-Inspired Nanotechnology The lotus plant’s magnificent ability to repel dirt has inspired a range of self-cleaning and antibacterial technologies that may also help control microfluidic "lab-on-a-chip" devices’, *Scientific American* Available at: http://insurftech.com/wp-content/uploads/2016/10/1.pdf (Accessed: 3 October 2017).

Fredman, C. (2002) ‘*The IDEO difference*’ Available at: http://5a5f89b8e10a225a44ac-ccbed124c38c4f7a3066210c073e7d55.r9.cf1.rackcdn.com/files/pdfs/news/hemispheres_1.pdf (Accessed: 15 December 2017).

Friedler, E. (2004) ‘Quality of Individual Domestic Greywater Streams and its Implication for On-Site Treatment and Reuse Possibilities’, *Environmental Technology*, 25(9) Taylor & Francis Group , pp. 997–1008. Available at: 10.1080/09593330.2004.9619393 (Accessed: 12 June 2017).

Furue, N. and Washida, Y. (2014) ‘Conception of the Inductive Reverse Innovation by Developed-Country Multinational Enterprises’, *2014 Proceedings of PICMET ’14: Infrastructure and Service Integration* Available at: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6921127 (Accessed: 7 December 2017).

Gajendra K. Verma, Christopher Bagley, M.J. (2007) *International Perspectives on Educational Diversity and Inclusion: Studies ... - Google Books*. Available at: https://books.google.co.uk/books?hl=en&lr=&id=oYt9AgAAQBAJ&oi=fnd&pg=PA181&dq=dhalit+faeces&ots=wrVwLJP5gk&sig=DXXT79AWCYwfuNpmJ0PN-Zn8fJU#v=onepage&q=faeces&f=false (Accessed: 3 August 2017).

Garcia, R. and Calantone, R. (2002) ‘A critical look at technological innovation typology and innovativeness terminology: a literature review’, *Journal of Product Innovation Management*, 19(2) Blackwell

Publishing, pp. 110–132. Available at: 10.1111/1540-5885.1920110 (Accessed: 25 September 2017).

Gauley, B. (2016a) '*Maximum Performance (MaP) Testing Toilet Fixture Performance Testing Protocol*' Available at: http://www.map-testing.com/assets/files/MaP test protocol Version 6 - June 2016 Final.pdf (Accessed: 13 June 2017).

Gauley, B. (2016b) *MaP testing. 1.06 gallons*. Available at: http://www.map-testing.com/assets/reports/1.06 gallon toilets...why not.pdf (Accessed: 1 October 2017).

Van der Geest, S. (2007) 'Not knowing about defecation', *On knowing & not knowing in the anthropology of medicine*, , pp. 75–86.

Van Der Geest, S. (2002) 'The night-soil collector: Bucket latrines in Ghana', *Postcolonial Studies*, 5(2), pp. 197–206. Available at: 10.1080/1368879022000021092 (Accessed: 31 January 2017).

George, R. (2008) *The Big Necessity: Adventures in the World of Human Waste: Amazon.co.uk: Rose George: 9781846270697: Books*. london.

Georgilas, I.P. and Tourassis, V.D. (2007) '*qulaity issues in enameing of ceramic industry products*', Available at: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=4419387 (Accessed: 2 October 2017).

Glavan, C. et al. (2013) 'Omniphobic " R F Paper " Produced by Silanization of Paper with Fluoroalkyltrichlorosilanes', *Advanced Functional Materials*, 24(1), pp. 60–70. Available at: 10.1002/adfm (Accessed: 11 November 2017).

Goffin, K. et al. (2010) *Identifying Hidden Needs: Creating Breakthrough Products*. Palgrave Macmillan. Available at: https://books.google.com/books?hl=en&lr=&id=wUnmLXrTXgwC&pgis=1 (Accessed: 11 August 2015).

Goffin, K. et al. (2012) 'Beyond the Voice of the Customer', *Research-Technology Management* Available at: file:///C:/Users/s203465/Downloads/out (1).pdf (Accessed: 27 November 2017).

Gogolides, E. et al. (2015) 'Hierarchical micro and nano structured, hydrophilic, superhydrophobic and superoleophobic surfaces incorporated in microfluidics, microarrays and lab on chip microsystems’, *Microelectronic Engineering*, 132 Elsevier, pp. 135–155. Available at: 10.1016/J.MEE.2014.10.002 (Accessed: 4 October 2017).

Govindarajan (2012) ‘Conversations: Reverse Innovation: An Interview with Vijay Govindarajan’, *Research-Technology Management*, 55(6) Available at: 10.5437/08956308X5506003 (Accessed: 10 August 2017).

Govindarajan, V. and Euchner, J. (2012) ‘Reverse Innovation’, *Research-Technology Management*, 55(6) Routledge, pp. 13–17.

Govindarajan, V. and Ramamurti, R. (2011) ‘Reverse innovation, emerging markets, and global strategy’, *Global Strategy Journal*, 1(3–4), pp. 191–205. Available at: 10.1002/gsj.23 (Accessed: 19 August 2015).

Govindarajan, V. and Trimble, C. (2013) *Reverse Innovation: Create Far From Home, Win Everywhere*. Harvard Business Press. Available at: https://books.google.com/books?hl=en&lr=&id=8xndLK8ZbxcC&pgis=1 (Accessed: 4 August 2015).

Greenland, K. et al. (2016) ‘A cross-sectional survey to assess household sanitation practices associated with uptake of "Clean Team" serviced home toilets in Kumasi, Ghana’, *Environment and Urbanization*, SAGE Publications, p. 956247816647343. Available at: 10.1177/0956247816647343 (Accessed: 7 July 2016).

Guiteras, R. et al. (2015) ‘Sanitation subsidies. Encouraging sanitation investment in the developing world: a cluster-randomized trial.’, *Science (New York, N.Y.)*, 348(6237) American Association for the Advancement of Science, pp. 903–6. Available at: 10.1126/science.aaa0491 (Accessed: 26 July 2016).

Gunawardana, I.P.P. and Galagedara, L.W. (2013) ‘A new approach to measure sanitation performance’, *Journal of Water Sanitation and Hygiene for Development*, 3(2), pp. 269–282.

Hadengue, M. et al. (2017) ‘A Systematic Literature Review Reverse Innovation A Systematic Literature Review’, *International Journal of*

Emerging Markets International Journal of Emerging Markets Iss, 12(5), pp. 5–11. Available at: http://dx.doi.org/10.1108/IJoEM-12-2015-0272 (Accessed: 6 December 2017).

Hall, D. (2007) ‘Fail fast, fail cheap’, *business week* Available at: http://wp.programdoctor.com/wp/wp-content/uploads/2013/03/FailFast.pdf (Accessed: 1 October 2017).

Health and Safety Executive (2011) *Health and Safety Executive Working with sewage*. Available at: http://www.hse.gov.uk/pubns/indg198.pdf (Accessed: 27 June 2017).

Health and Safety Executve (1991) *Safe working and the prevention of infection in clinical laboratories and similar facilities HSE Books Health and Safety Executive Health and Safety Executive*. Available at: http://www.hse.gov.uk/pubns/clinical-laboratories.pdf (Accessed: 31 October 2017).

Heijnen, M. et al. (2014) ‘Shared Sanitation versus Individual Household Latrines: A Systematic Review of Health Outcomes’, *PLoS ONE*, 9(4) Public Library of Science, p. e93300. Available at: 10.1371/journal.pone.0093300 (Accessed: 27 June 2016).

Hensel, R. et al. (2016) ‘The springtail cuticle as a blueprint for omniphobic surfaces’, *Chem. Soc. Rev.*, 45(2) Royal Society of Chemistry, pp. 323–341. Available at: 10.1039/C5CS00438A (Accessed: 3 October 2017).

Hermans, D. et al. (2013) *Changing emotions*. Available at: https://books.google.co.uk/books?hl=en&lr=&id=iGPXpX3ST2sC&oi=fnd&pg=PA74&dq=odour+faeces+toilet+neutrali*&ots=873Y-Yuv-4&sig=ao9ypew_j9WNZnAtGoSxI-arp5E#v=onepage&q=odour faeces toilet neutrali*&f=false (Accessed: 22 October 2017).

Hickman, L. (2010) *Why don’t we use urinals in the home?*., *Guardian Newspaper online*

Hindustan Times (2017) *Akshay Kumar empties toilet pit with Madhya Pradesh minister | bollywood | Hindustan Times*., *Hidustantimes* Available at: http://www.hindustantimes.com/bollywood/akshay-kumar-empties-toilet-pit-with-madhya-pradesh-minister/story-geWeGJYjfr0vth5ZCeqgUJ.html (Accessed: 3 August 2017).

von Hippel, E. (1986) Lead Users: A Source of Novel Product

Concepts *Management Science*.

Hulland, K.R. et al. (2013) ‘Designing a handwashing station for infrastructure-restricted communities in Bangladesh using the integrated behavioural model for water, sanitation and hygiene interventions (IBM-WASH)’, *BMC Public Health*, 13 Available at: 10.1186/1471-2458-13-877 (Accessed: 12 July 2017).

IDEO.org (2011) *The Problem – Clean Team Ghana*., *The Problem* Available at: http://cleanteamtoilets.com/the-problem/ (Accessed: 6 September 2015).

IDEO.org (2015) *The Field Guide to Human-Centred Design*. Available at: file:///C:/Users/s203465/Documents/PhD/articles. paper 1/Field Guide to Human-Centered Design_IDEO.pdf (Accessed: 14 November 2017).

Immelt, J.R. et al. (2009) ‘How GE is disrupting itself’, *Harvard Business Review*, 87(10)

Ingle, A.R. et al. (2012) ‘Ingle_2012_What does it take to convince decision makers in’, *Fourth International Dry Toilet Conference, Tampere, Finland*, , pp. 1–8.

Jenkins, M. and Sugden, S. (2006) *Rethinking Sanitation: Lessons and Innovation for Sustainability and Success in the New Millennium*., *UNDP HDR2006 - Sanitation Thematic Paper* Available at: http://hdr.undp.org/sites/default/files/jenkins_and_sugden.pdf (Accessed: 12 May 2016).

Jenkins, M.W. and Scott, B. (2007) ‘Behavioral indicators of household decision-making and demand for sanitation and potential gains from social marketing in Ghana’, *Social Science & Medicine*, 64, pp. 2427–2442.

Jenssen, P.D. et al. (2003) ‘*LOCAL RECYCLING OF WASTEWATER AND WET ORGANIC WASTE – A STEP TOWARDS THE ZERO EMISSION COMMUNITY*’, A, pp. 8–10.

Jiang, H. et al. (2004) ‘Plasma-enhanced deposition of silver nanoparticles onto polymer and metal surfaces for the generation of antimicrobial characteristics’, *Journal of Applied Polymer Science*, 93(3) Wiley Subscription Services, Inc., A Wiley Company, pp. 1411–1422. Available at: 10.1002/app.20561 (Accessed: 7 July 2017).

JMP (2014) *Progress on drinking water and sanitation, 2014 Update - Resources • SuSanA*., *Progress on drinking water and sanitation, 2014 Update - Resources • SuSanA* Available at: http://www.susana.org/en/resources/library/details/2036 (Accessed: 30 November 2015).

Johns, R. (2010) *Likert items and scales*. Available at: file:///C:/Users/s203465/Downloads/likert_scale.pdf (Accessed: 20 September 2017).

Judge, B.M. et al. (2015) ‘Developing World Users as Lead Users: A Case Study in Engineering Reverse Innovation’, *Journal of Mechanical Design*, 137(7) American Society of Mechanical Engineers (ASME), p. 71406. Available at: 10.1115/1.4030057 (Accessed: 5 August 2015).

Karamchandani, A. et al. (2011) ‘Is the Bottom Of the Pyramid Really for You ? Is the Bottom Of the Pyramid Really for You ?’, *Harvard business review*, (March)

Katukiza, A.Y. et al. (2012) ‘Sustainable sanitation technology options for urban slums.’, *Biotechnology advances*, 30(5), pp. 964–78. Available at: 10.1016/j.biotechadv.2012.02.007 (Accessed: 10 May 2016).

Katukiza, A.Y. et al. (2010a) ‘Selection of sustainable sanitation technologies for urban slums--a case of Bwaise III in Kampala, Uganda.’, *The Science of the total environment*, 409(1), pp. 52–62. Available at: 10.1016/j.scitotenv.2010.09.032 (Accessed: 27 April 2015).

Katukiza, a. Y. et al. (2010b) ‘Selection of sustainable sanitation technologies for urban slums - A case of Bwaise III in Kampala, Uganda’, *Science of the Total Environment*, 409(1) Elsevier B.V., pp. 52–62.

Kennedy-Walker, R. et al. (2014) ‘Challenges for the future of urban sanitation planning: critical analysis of John Kalbermatten’s influence’, *Journal of Water, Sanitation and Hygiene for Development*, 4(1) IWA Publishing, p. 1. Available at: 10.2166/washdev.2013.164 (Accessed: 18 August 2016).

Keraita, B. et al. (2003) ‘Influence of urban wastewater on stream water quality and agriculture in and around Kumasi, Ghana', *Environment and Urbanization*, 15(2) Sage PublicationsSage CA: Thousand Oaks, CA, pp. 171–178. Available at: 10.1177/095624780301500207 (Accessed: 5 February 2017).

Keraita, B. et al. (2013) 'Accelerating uptake of household latrines in rural communities in the Volta region of Ghana', *Journal of Water, Sanitation and Hygiene for Development*, 3(1), p. 26.

Kone, D. (2012) *Water Sanitation and Hygiene: Reinvent the Toilet Challenge*. Available at: http://ma.ecsdl.org/content/MA2012-01/4/79.full.pdf (Accessed: 12 September 2017).

Kulich, D.M. et al. (2001) 'Acrylonitrile-Butadiene-Styrene Polymers', in *Encyclopedia of Polymer Science and Technology*. Hoboken, NJ, USA: John Wiley & Sons, Inc. Available at: 10.1002/0471440264.pst011 (Accessed: 7 November 2017).

Kvarnström, E. (2006) *Urine diversion : one step towards sustainable sanitation*. Stockholm Environment Institute. Available at: https://books.google.co.uk/books?hl=en&lr=&id=3JfWwl8iE10C&oi=fnd&pg=PR6&dq=sustainable+sanitation+sawdust&ots=JroDfV0n0z&sig=idE0KEfVp0h6aVdU1wAbNGmZIoU#v=onepage&q=sawdust&f=false (Accessed: 17 November 2017).

Kvarnström, E. et al. (2011) 'Chalmers Publication Library The Sanitation Ladder – a Need for a Revamp? The Sanitation Ladder – a Need for a Revamp?', *Journal of Water Sanitation and Hygiene for Development*, 1(1), pp. 2043–9083. Available at: 10.2166/washdev.2011.014 (Accessed: 8 August 2016).

Kwiringira, J. et al. (2014) 'Gender variations in access, choice to use and cleaning of shared latrines; experiences from Kampala Slums, Uganda', *BMC Public Health* Available at: 10.1186/1471-2458-14-1180 (Accessed: 19 November 2017).

Langergraber, G. and Muellegger, E. (2005) 'Ecological Sanitation—a way to solve global sanitation problems?', *Environment International*, 31(3), pp. 433–444. Available at: 10.1016/j.envint.2004.08.006 (Accessed: 25 May 2017).

Larsen, T. A., Udert, K. M., & Lienert, J. (2013) *Source separation and decentralization for wastewater management.* IWA Publishing.

Larsson, E. and Nilsson, M. (2013) *Towards sustainable sanitation in slum areas*. Available at: http://www.diva-portal.org/smash/get/diva2:640967/FULLTEXT01.pdf (Accessed: 12 September 2017).

Laughlin, Z. (2011) *Material matters*. Available at: file:///C:/Users/s203465/Downloads/Material Matters_ZoeLaughlin (1).pdf (Accessed: 10 November 2017).

Lee, H.S. and Lee, K.-W. (2003) ‘Practical Case Study of Resolving the Physical Contradiction in TRIZ; Super Water-Saving Toilet System Using Flexible Tube’, *TRIZ journal* Available at: http://www.metodolog.ru/triz-journal/archives/2003/11/e/05.pdf (Accessed: 2 October 2017).

Lefteri, C. (2008) *The plastics handbook*. RotoVision.

Lentle, R. and Janssen, P.W.M. (2011) *The physical processes of digestion*. Springer. Available at: https://books.google.co.uk/books?id=kN1edFo-1bUC&pg=PA99&lpg=PA99&dq=faeces+viscoelastic&source=bl&ots=xHHLh689Dt&sig=DIS0ryfK26oin-47RRTS-0E3J4c&hl=en&sa=X&ved=0ahUKEwj764uC_fXWAhUkAsAKHa8bAAMQ6AEIMjAC#v=onepage&q=faeces viscoelastic&f=false (Accessed: 16 October 2017).

Lerouge, C. et al. (2013) ‘User profiles and personas in the design and development of consumer health technologies’, *International Journal of Medical Informatics*, 82, pp. e251–e268. Available at: 10.1016/j.ijmedinf.2011.03.006 (Accessed: 28 November 2017).

Lewandowski, M. and Mateusz (2016) ‘Designing the Business Models for Circular Economy—Towards the Conceptual Framework’, *Sustainability*, 8(1) Multidisciplinary Digital Publishing Institute, p. 43. Available at: 10.3390/su8010043 (Accessed: 29 September 2017).

Lewis, S.J. and Heaton, K.W. (1997) ‘Stool form scale as a useful guide to intestinal transit time.’, *Scandinavian journal of gastroenterology*, 32(9), pp. 920–4. Available at: 10.3109/00365529709011203 (Accessed: 6 July 2016).

Lienert, J. and Larsen, T. (2010) ‘High Acceptance of Urine Source Separation in Seven European Countries: A Review’, *Environmental*

Science & Technology

Lim, Y.A.L. and Vythilingam, I. (2014) *Parasites and their vectors : a special focus on Southeast Asia*. Available at: https://books.google.co.uk/books?id=-De8BAAAQBAJ&pg=PA218&lpg=PA218&dq=One+gram+of+fresh+faeces+from+an+infected+person+can+contain+around+106+viral+pathogens,+106+–+108+bacterial+pathogens,+104+protozoan+cysts+or+oocysts+and+10-104+helminth+eggs&source=b (Accessed: 10 April 2017).

Littlewood, K. et al. (2007) 'Downstream implications of ultra-low flush WCs', *Water Practice and Technology*, 2(2) IWA Publishing, p. wpt2007037. Available at: 10.2166/wpt.2007.037 (Accessed: 28 May 2016).

Loowatt (2017a) *Technology Loowatt Luxury Waterless Toilet Technology*. Available at: http://loowatt.com/technology/ (Accessed: 8 June 2017).

Loowatt (2017b) *Global Sanitation Loowatt Luxury Waterless Toilet Technology*. Available at: https://loowatt.com/global-sanitation-madagascar-toilets/ (Accessed: 12 September 2017).

Lopez Zavala, M.A. and Funamizu, N. (2006) 'Design and operation of the bio-toilet system', *Water Science and Technology* Available at: 10.2166/wst.2006.277 (Accessed: 14 November 2017).

Mae, G. et al. (2016) 'Introducing Students to Gas Chromatography−Mass Spectrometry Analysis and Determination of Kerosene Components in a Complex Mixture', *Journal of chemical education* Available at: 10.1021/acs.jchemed.5b00830 (Accessed: 24 October 2017).

Mara, D. et al. (2010a) 'Sanitation and Health', *PLoS Medicine*, 7(11) Public Library of Science, p. e1000363. Available at: 10.1371/journal.pmed.1000363 (Accessed: 9 June 2016).

Mara, D. et al. (2010b) 'Sanitation and Health', *PLoS Medicine*, 7(11) Public Library of Science, p. e1000363. Available at: 10.1371/journal.pmed.1000363 (Accessed: 20 November 2017).

Marcus, H. et al. (1994) '*Solid freeform fabrication proceedings*', Available at: file:///C:/Users/s203465/Downloads/ADA290949.pdf

(Accessed: 1 October 2017).

Marmur, A. (2004) ‘The Lotus Effect : Superhydrophobicity and Metastability’, *American Chemical Society* Available at: 10.1021/la036369u (Accessed: 4 September 2017).

Martin, B. and Hanington, B.M. (2012) *Universal methods of design : 100 ways to research complex problems, develop innovative ideas, and design effective solutions*. Rockport Publishers.

McGranahan, G. (2001) *The citizens at risk : from urban sanitation to sustainable cities*. Earthscan. Available at: https://books.google.co.uk/books?hl=en&lr=&id=C5ZoMXPAIGcC&oi=fnd&pg=PR5&dq=urban+sanitation+in+cities+densely*+populated&ots=5eW_Z6RpsI&sig=zS3r6lDH2L-JgyXoKT3SY6C0P1g#v=onepage&q=cities&f=false (Accessed: 28 November 2017).

Mecca, S. et al. (2013a) ‘Application of GSAP Microflush toilets: a sustainable development approach to rural and peri-urban sanitation’, *WIT Transactions on Ecology and the Environment*. WIT Press, Vol.175, pp. 113–122. Available at: 10.2495/ECO130101 (Accessed: 25 July 2016).

Mecca, S. et al. (2013b) ‘*Application of GSAP Microflush toilets: a sustainable development approach to rural and peri-urban sanitation*’

Moe, C.L. and Rheingans, R.D. (2006) ‘Global challenges in water, sanitation and health’, *Journal of Water and Health*, 4(S1) IWA Publishing, pp. 41–57. Available at: http://jwh.iwaponline.com/content/4/S1/41.abstract (Accessed: 29 May 2016).

Moore, J.G. et al. (1987) ‘Gas-Chromatographic and Mass-Spectrometric Analysis of the Odor of Human Feces’, *GASTROENTEROLOGY*, 93, pp. 1321–9. Available at: http://www.gastrojournal.org/article/0016-5085(87)90262-9/pdf (Accessed: 25 October 2017).

Mugure, A. and Mutua, B.M. (2009) ‘Norms, attitudes and gender perspectives in ecological sanitation’, *Water, Sanitation and Hygiene: Sustainable Development and Multisectoral Approaches - Proceedings of the 34th WEDC International Conference*.

Myers, J. et al. (2016) '*CLTS Knowledge Hub Learning Brief Using a CLTS Approach in Peri- Urban and Urban Environments: Potential at Scale*' Available at: www.communityledtotalsanitation.org (Accessed: 6 August 2016).

Nagy, J. and Zseni, A. (2016) 'SWOT analysis of dry toilets', *Environmental Impact*

Narain, S. (2002) '*The flush toilet is ecologically mindless*'

Narracott, A. and Norman, G. (2011) '*Clean Team, a human-centred approach to sanitation: inital trails in Ghana*', , pp. 1–2.

Nawab, B. et al. (2006) 'Cultural preferences in designing ecological sanitation systems in North West Frontier Province, Pakistan', *Journal of Environmental Psychology*, 26, pp. 236–246.

Niwagaba, C. (2007) '*Institutionen för biometri och teknik Human Excreta Treatment Technologies – prerequisites, constraints and performance*'

Obeng, P.A. et al. (2015) 'Usage and Barriers to Use of Latrines in a Ghanaian Peri - Urban Community', *Environ . Process*, 2, pp. 261–274. Available at: 10.1007/s40710-015-0060-z (Accessed: 2 September 2017).

OECD (1991) 'The nature of innovation and the evolution of productive system', *technology and productivity*, 4(4), pp. 379–396. Available at: 10.1080/08941929109380768 (Accessed: 26 September 2017).

Ohki, T. et al. (2010) 'Characterization of Scale Formed on the Surfaces of Toilet Bowls', *Journal of Surfactants and Detergents*, 13(1) Springer-Verlag, pp. 19–26. Available at: 10.1007/s11743-009-1147-1 (Accessed: 31 March 2017).

Oki, T. (2003) 'Global water resources assment under climatic change in 2050 using TRIP', *Resources systems*, (280), p. 129.

Okurut, K. et al. (2015) '*Assessing demand for improved sustainable sanitation in low-income*' Available at: http://epubs.surrey.ac.uk/806428/9/Assessing demand.pdf (Accessed: 14 December 2017).

Osakue, E.E. (2013) '*Teaching SI Units in Engineering and Technology Programes*', Available at: file:///C:/Users/s203465/Downloads/TEACHING_SI.pdf (Accessed: 17 October 2017).

Otterpohl, R. et al. (2003) '*Innovative technologies for decentralised water-, wastewater and biowaste management in urban and peri-urban areas*' Available at: http://wst.iwaponline.com/content/ppiwawst/48/11-12/23.full.pdf (Accessed: 20 November 2017).

Packham, D.E. (2003) 'Surface energy,surface topography and adhesion', *International Journal of Adhesion & Adhesives 23* Available at: https://ac.els-cdn.com/S014374960300068X/1-s2.0-S014374960300068X-main.pdf?_tid=139ec300-b299-11e7-a909-00000aab0f26&acdnat=1508175799_453ad4adde2e1d5ae1513a7c856e74ab (Accessed: 16 October 2017).

Pal, S.B. (1990) *Handbook of Laboratory Health and Safety Measures*. Springer Netherlands. Available at: https://books.google.co.uk/books?id=MhTvCAAAQBAJ&pg=PA83&lpg=PA83&dq=health+and+safety+laboratory+faeces+hepatitis+vaccination&source=bl&ots=tcWPIMnwsj&sig=nl6uE6wOFluEVODg1hRbMLCSXZs&hl=en&sa=X&ved=0ahUKEwiYnZHK0JrXAhXDtRoKHXQnDmkQ6AEISzAG#v=onepage&q=he (Accessed: 31 October 2017).

Papanek, V. and Fuller, R.B. (1982) *DESIGN FOR THE REAL WORLD*. London: Thames and Hudson.

Parker, A. (2014) 'Membrane technology plays key role in waterless hygienic toilet', *Membrane Technology*, 2014(12), p. 8. Available at: 10.1016/S0958-2118(14)70255-1 (Accessed: 8 September 2017).

Parkin, I.P. and Palgrave, R.G. (2005) 'Self-cleaning coatings', *Journal of Materials Chemistry*, 15(17) Royal Society of Chemistry, p. 1689. Available at: 10.1039/b412803f (Accessed: 2 October 2017).

Patel, D. et al. (2011) 'Excreta disposal in emergencies: Bag and Peepoo trials with internally displaced people in Port-au-Prince', *Waterlines*, 30(1) Available at: 10.3362/1756-3488.2011.006 (Accessed: 8 June 2017).

Paterson, C. et al. (2007) ‘Pro-poor sanitation technologies’, *Geoforum*, 38(5), pp. 901–907.

Pekarek, S. (2003) ‘Non-thermal plasma ozone generation’, *Acta Polytechnica* Available at: https://ojs.cvut.cz/ojs/index.php/ap/article/viewFile/498/330 (Accessed: 24 October 2017).

Practical Action (2004) *Ventialated improved pit latrine*. Available at: file:///C:/Users/s203465/Downloads/4f7cf4c7-9b90-4ff0-b5b3-186e1661b3dc (1).pdf (Accessed: 8 November 2017).

Proença, L.C. et al. (2011) ‘Potential for electricity savings by reducing potable water consumption in a city scale’, *Resources, Conservation and Recycling*, 55(11), pp. 960–965. Available at: 10.1016/j.resconrec.2011.05.003 (Accessed: 23 November 2015).

PSI (2016) *Vacuum flush EVAC toilet report: Siemens UK Limited*. waterloovile.

Purves, I. and Gardiner, V. (2013) *Culturally and financially sustainable appplications of Loowatt technology in Antananarivo, Madagascar - early feedback*. Available at: http://www.loowatt.com/wp-content/uploads/2012/10/Loowatt_FSM2_Paper.pdf (Accessed: 12 September 2017).

Quitzau, M.-B. (2007) ‘Water-flushing toilets: Systemic development and path-dependent characteristics and their bearing on technological alternatives’, *Technology in Society*, 29(3), pp. 351–360. Available at: 10.1016/j.techsoc.2007.04.005 (Accessed: 12 May 2016).

Radford, J.T. et al. (2015) ‘*Faecal sludge simulants to aid the development of desludging technologies*’

Rajagopal, R. et al. (2013) ‘Anaerobic co-digestion of source segregated brown water (feces-without-urine) and food waste: For Singapore context’, *Science of the Total Environment*, 443, pp. 877–886.

Ramani, S. V. et al. (2016) ‘Catalysing innovation for social impact: The role of social enterprises in the Indian sanitation sector’, *Technological Forecasting and Social Change*

Rao et al. (2016) *Business models for fecal sludge management - Rao, Krishna C., Kvarnstrom, E., Di Mario, L., Drechsel, Pay - Google Books*. Available at: https://books.google.co.uk/books?id=HvmkDQAAQBAJ&pg=PA44&lpg=PA44&dq=dry+sanitation+x+runner+soil+haiti&source=bl&ots=fjSjElHF6G&sig=SI2IHuhuURvGQg8OV6Ii6yfwBOU&hl=en&sa=X&ved=0ahUKEwi52YHx7dbVAhWMBsAKHeXBCdMQ6AEIOTAG#v=onepage&q=dry sanitation x ru (Accessed: 14 August 2017).

Rheinlander, T. et al. (2013) 'Smell: an overlooked factor in sanitation promotion', *Waterlines*, 32(2)

Rieck, C. et al. (2012) *Technology review of urine-diverting dry toilets (UDDTs) - Resources • SuSanA*. Available at: http://www.susana.org/en/resources/library/details/874 (Accessed: 30 March 2017).

Roca (2016) *Roca Group // ASIA-PACIFIC*. Available at: http://www.roca.com/memoria_roca_2014/asia_pacific.html (Accessed: 6 December 2017).

Rogers, E.M. (2010) *Diffusion of Innovations, 4th Edition*. Simon and Schuster. Available at: https://books.google.com/books?hl=en&lr=&id=v1ii4QsB7jIC&pgis=1 (Accessed: 30 November 2015).

Roma, E. et al. (2010) 'Assessing users' experience of shared sanitation facilities: A case study of community ablution blocks in Durban, South Africa', *Water SA*, 36(5) Available at: 10.4314/wsa.v36i5.61992 (Accessed: 13 December 2017).

Roma, E. et al. (2013) 'User perceptions of urine diversion dehydration toilets: Experiences from a cross-sectional study in eThekwini Municipality', *Print) = Water SA*, 39(2) Available at: 10.4314/wsa.v39i2.15 (Accessed: 15 August 2017).

Rose, C. et al. (2015a) 'The Characterization of Feces and Urine: A Review of the Literature to Inform Advanced Treatment Technology.', *Critical reviews in environmental science and technology*, 45(17) Taylor & Francis, pp. 1827–1879. Available at: 10.1080/10643389.2014.1000761 (Accessed: 18 July 2015).

Rose, C. et al. (2015b) 'The Characterization of Feces and Urine: A

Review of the Literature to Inform Advanced Treatment Technology.', *Critical reviews in environmental science and technology*, 45(17) Taylor and Francis Inc., pp. 1827–1879. Available at: 10.1080/10643389.2014.1000761 (Accessed: 30 November 2015).

Royte, E. (2017) Nearly a Billion People Still Defecate Outdoors. Here's Why., *National Geographic*, Available at: https://www.nationalgeographic.com/magazine/2017/08/toilet-defecate-outdoors-stunting-sanitation/ (Accessed: 11 November 2017).

Sah, S. and Negussie, A. (2009) 'Community led total sanitation (CLTS): Addressing the challenges of scale and sustainability in rural Africa', *Desalination*, 248(1–3) Elsevier, pp. 666–672. Available at: 10.1016/j.desal.2008.05.117 (Accessed: 18 August 2016).

Sato, H. et al. (2002) 'Analysis of Malodorous Substances of Human Feces', *Journal of Health Science*, 48(2), pp. 179–185.

Satterthwaite, D. and Mcgranahan, G. (2006) '*Human Development Report 2006 Overview of the Global Sanitation Problem*' Available at: http://hdr.undp.org/sites/default/files/satterthwaite_mcgranahan.pdf (Accessed: 26 November 2017).

Schertenleib, R. et al. (2003) 'Guidelines for the Implementation of the Bellagio Principles and the Household-Centred Environmental Sanitation Approach (HCES)', *Proceedings of the 2nd international Symposium on Ecological Sanitation*, , p. 8. Available at: http://www.eawag.ch/forschung/sandec/publikationen/sesp/dl/Schertenleib_Morel_Kalbermatten_2003.pdf (Accessed: 18 August 2016).

Schlosser, C.A. et al. (2014) 'The future of global water stress: An integrated assessment', *Earth's Future*, 2(8), pp. 341–361. Available at: 10.1002/2014EF000238 (Accessed: 23 November 2015).

Schneider, C.A. et al. (2012) 'NIH Image to ImageJ: 25 years of image analysis', *Nature Methods*, 9(7), pp. 671–675. Available at: 10.1038/nmeth.2089 (Accessed: 13 December 2017).

Seleman, A. and Bhat, M.G. (2016) '*Multi-criteria assessment of sanitation technologies in rural Tanzania: Implications for program implementation, health and socio-economic improvements*' Available at: 10.1016/j.techsoc.2016.04.003 (Accessed: 8 November 2017).

Seo, Y. and Seouk Park, I. (2013) ‘Study for flow and mass transfer in toilet bowl by using toilet seat adopting odor/bacteria suction feature’, *Building and Environment*, 67, pp. 46–55.

Seymour, Z. and Hughes, J. (2014) ‘Sanitation in developing Seymour, Z., & Hughes, J. (2014). Sanitation in developing countries: a systematic review of user preferences and motivations. Journal of Water, Sanitation and Hygiene for Development, 4(4), 681. http://doi.org/10.2166/washdev.201’, *Journal of Water, Sanitation and Hygiene for Development*, 4(4) IWA Publishing, p. 681. Available at: 10.2166/washdev.2014.127 (Accessed: 27 June 2016).

Siddiqui, A. et al. (2010) ‘An experimental and theoretical study of the effect of sample thickness on the Shore hardness of elastomers’, *Dental Materials*, 26, pp. 560–564. Available at: 10.1016/j.dental.2010.02.004 (Accessed: 20 October 2017).

Siegel, R.P. (2015) ‘Energy otherwise flushed away: a waterless toilet can provide the feedstock for a biogas digester’, *Mechanical Engineering-CIME*, 137(9) American Society of Mechanical Engineers, pp. 10–12.

Sikirov, D. (2003) ‘Comparison of Straining During Defecation in Three Positions: Results and Implications for Human Health’, *Digestive Diseases and Sciences*, 48(7) Kluwer Academic Publishers-Plenum Publishers, pp. 1201–1205. Available at: 10.1023/A:1024180319005 (Accessed: 7 February 2017).

Simanis, E. and Hart, S. (2008) ‘The Base of the Pyramid Protocol: Toward Next Generation BoP Strategy’, *Innovations: Technology, Governance, Globalization*, 3(1), pp. 57–84.

Son, J. and Shu, L.H. (2012) ‘Leveraging technology for a sustainable world : proceedings of the 19th CIRP Conference on Life Cycle Engineering, University of California at Berkeley, Berkeley, USA, May 23-25,’ *role of transformation Principles in enabling environmentally significant behaviour*. Available at: https://www.google.co.uk/_/chrome/newtab?espv=2&ie=UTF-8 (Accessed: 16 October 2017).

De Sousa, B.M. and Marcos, P. (2016) *DOMESTOS: IN THE UK TOILET CLEANERS MARKET DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF REQUIREMENTS FOR THE DEGREE*

OF MSc IN MANAGEMENT, AT UNIVERSIDADE CATÓLICA PORTUGUESA. Available at: http://repositorio.ucp.pt/bitstream/10400.14/21077/1/Master_Thesis_Bernardo_Final.pdf (Accessed: 2 October 2017).

Stratasys (2016) *3D Printing: Laser Sintering vs. Fused Deposition Modeling*. Available at: https://www.stratasysdirect.com/blog/sls-vs-fdm-3d-printing/ (Accessed: 1 October 2017).

Sugden, S. (2014) 'Latrine design: go in peace', *Waterlines*, 33(3), pp. 220–239. Available at: 10.3362/1756-3488.2014.023 (Accessed: 8 February 2017).

Sun Mar (2017) *Composting Toilets by Sun-Mar - Our Company History*. Available at: http://www.sun-mar.com/comp_mile.html (Accessed: 4 December 2017).

Swann, P. et al. (2007) *Sanitation Policy Background Paper. Water is Life, Sanitation is Dignity*.

Szczygiel, M. (2016) '*From Night Soil to Washlet*', electronic journal of contemporary japanese studies Available at: http://japanesestudies.org.uk/ejcjs/vol16/iss3/szczygiel.html (Accessed: 16 October 2017).

Tang, C.Y. et al. (2011) 'Fabrication of antibacterial silicone composite by an antibacterial agent deposition, solution casting and crosslinking technique', *Polymer International*, 60(10) John Wiley & Sons, Ltd., pp. 1461–1466. Available at: 10.1002/pi.3102 (Accessed: 5 October 2017).

Teh, T.-H. (2013) 'Bypassing the flush, creating new resources: analysing alternative sanitation futures in London', *Local Environment*, 20(3) Routledge, pp. 335–349. Available at: 10.1080/13549839.2013.847409 (Accessed: 19 November 2015).

Thomas, K.D. (2015) *Handbook of research on sustainable development and economics*. Available at: https://books.google.co.uk/books?hl=en&lr=&id=GIYfCgAAQBAJ&oi=fnd&pg=PA1&dq=urban+sanitation+1.5+million+childhood&ots=0aau1ey-Pj&sig=PsHCym0RAWrWp8NLFxQYFbd0K7M#v=onepage&q&f=false (Accessed: 7 December 2017).

Thompson, R. (Designer) (2007) *Manufacturing processes for design professionals*. Thames & Hudson.

Tierney, R. (2014) *The Development of the User Interface of an Innovative Sanitation Solution Targeted at Developing Countries*. Cranfield University.

Tobias, R. et al. (2017) ‘Early testing of new sanitation technology for urban slums: The case of the Blue Diversion Toilet’, *Science of The Total Environment*, 576, pp. 264–272. Available at: 10.1016/j.scitotenv.2016.10.057 (Accessed: 13 October 2017).

TOTO (2014) *TOTO Americas*.

Tripsas, M. et al. (2009) *Toto: The Bottom Line*

Tsibouklis, J. and Nevell, T.G. (2003) ‘Ultra-Low Surface Energy Polymers: The Molecular Design Requirements’, *Advanced Materials*, 15(78) WILEY-VCH Verlag, pp. 647–650. Available at: 10.1002/adma.200301638 (Accessed: 1 September 2017).

Ulrich, K.T. and Eppinger, S.D. (2000) *Product design and development*. Irwin/McGraw-Hill.

UN (2016) *The Sustainable Development Goals Report*. New York.

UN-HABITAT (2007) *State of the World’s cities*.

UNICEF/WHO (2008) *Progress on drinking water and sanitation*.

Vinnerås, B. et al. (2009) ‘Peepoo bag: self-sanitising single use biodegradable toilet’, *Water Science and Technology*, 59(9) Available at: http://wst.iwaponline.com/content/59/9/1743 (Accessed: 26 May 2017).

Wang, J. and Ondrey, G. (2016) *Engineering surfaces to repel all liquids*., *Chemical engineering* Available at: https://www.scribd.com/document/356596394/July-2016-International-pdf (Accessed: 17 October 2017).

Werner, C. et al. (2000) ‘*ecosan – closing the loop in wastewater management and sanitation*’, , pp. 30–31. Available at: http://www.indiawaterportal.org/sites/indiawaterportal.org/files/ecosan_cd/material/D_recommended-reading/06_conference-proceedings/03-other/en-proceedings-1st-international-ecosan-symposium-2000.pdf#page=38 (Accessed: 19 November 2017).

West, S. (2001) '*INNOVATIONS FROM SCANDINAVIA: INCREASING THE POTENTIAL FOR REUSE*', Available at: http://waterfund.go.ke/watersource/Downloads/006. Innovations Scandinavia.pdf (Accessed: 19 November 2017).

WHO (2009) 'Diarrhoea : why children are still dying and what can be done', *WHO*, Geneva : World Health Organization

WHO (2016) 'WHO | Global Report on Urban Health', *WHO*, World Health Organization

WHO (2017) '*Progress on Drinking Water, Sanitation and Hygiene*' Available at: http://www.wipo.int/amc/en/ (Accessed: 15 August 2017).

WHO and UNICEF (2016) '*Drinking Water and Sanitation 2014 UPDATE*'

Wignarajah, K. et al. (2006) '*Simulated Human Feces for Testing Human Waste Processing Technologies in Space Systems*', Available at: 10.4271/2006-01-2180 (Accessed: 4 September 2017).

Williams, L. et al. (2010) 'The role of risk perception in reducing cholera vulnerability', *Risk Management*, 12(12), pp. 1460–3799. Available at: 10.1057/rm.2010.1 (Accessed: 29 July 2016).

Winblad, U. et al. (2004) *Ecological sanitation*. Available at: http://www.ecosanres.org/pdf_files/Ecological_Sanitation_2004.pdf (Accessed: 3 August 2017).

Winter, A.G. et al. (2009) '*THE DESIGN AND TESTING OF A LOW-COST, GLOBALLY-MANUFACTURABLE, MULTI-SPEED MOBILITY AID DESIGNED FOR USE ON VARIED TERRAIN IN DEVELOPING AND DEVELOPED COUNTRIES*' Available at: file:///C:/Users/s203465/Downloads/657_1 (2).pdf (Accessed: 21 November 2017).

Winter, A.G. et al. (2013) 'Stakeholder-Driven Design Evolution of the Leveraged Freedom Chair Developing World Wheelchair', *American Society of Mechanical Engineers (ASME)*, ASME Available at: https://dspace.mit.edu/handle/1721.1/108770 (Accessed: 20

November 2017).

Wolcott, H.F. (2005) *The art of fieldwork*. Altamira Press. Available at: https://books.google.co.uk/books/about/The_Art_of_Fieldwork.html?id=qcxanF633RoC (Accessed: 12 July 2017).

Wong, T.-S. et al. (2011) 'Bioinspired self-repairing slippery surfaces with pressure-stable omniphobicity.', *Nature*, 477(7365) Nature Publishing Group, a division of Macmillan Publishers Limited. All Rights Reserved., pp. 443–7. Available at: 10.1038/nature10447 (Accessed: 15 July 2015).

Woolley, S. et al. (2014) 'Shear rheological properties of fresh human faeces with different moisture content', *Print) = Water SA*, 40(2) Available at: 10.4314/wsa.v40i2.9 (Accessed: 17 October 2017).

Wsup (2007) '*Community-Led Total Sanitation in Rural Areas*'

WSUP (2016) *Improving the quality of public toilet services in Kumasi | Sanitation Updates*. Available at: https://sanitationupdates.wordpress.com/2016/07/21/improving-the-quality-of-public-toilet-services-in-kumasi/ (Accessed: 13 February 2017).

Yu, Y. et al. (2007) '*Mechanical and Superhydrophobic Stabilities of Two - Scale Surfacial Structure of Lotus Leaves*' Available at: 10.1021/la7003485 (Accessed: 5 September 2017).

von Zedtwitz, M. et al. (2015) 'A Typology of Reverse Innovation', *Journal of Product Innovation Management*, 32(1), pp. 12–28. Available at: 10.1111/jpim.12181 (Accessed: 13 March 2015).

APPENDICES

The following pages detail the content that was not suitable for the main report but potentially still valuable as supporting information to compliment the body of the thesis.

A.1 – Repulsion to faeces in different cultures

The degree of repulsion to faeces can vary between cultures and further more on an individual basis of people within each culture. A strong example of a 'faecophobic' culture is within the Hindu community whereby waste is only handled by people in the lowest social class (caste) called Dhalit which means 'crushed' or 'broken'. Alternatively known as the 'untouchables', they have been involved with occupations that involved ritually impure activities for many generations (Gajendra K. Verma, Christopher Bagley, 2007). In rural China, for thousands of years, farmers have tended to their crops and fertilised the land with both fresh and composted excreta leading to human waste to be seen as valuable product. Even today the rural Chinese have very little disgust when discussing or coming in contact with faeces (Winblad et al., 2004). This lack of repulsion has perhaps lead to lack of incentive to have improved toilets. Upgrading sanitation in poor rural areas of China is a herculean task. Winblad explains that in semi-urban areas of China, people are building nice modern homes but sanitation is not being given any attention. 'A household can spend money on a luxury house with mirrors on the ceiling and marble on the floor, but the toilet is still an open stinking pit in the backyard' (Black and Fawcett, 2008; Winblad et al., 2004). The artist Andy Warhol wrote in 1975 about how having the president clean a toilet could break down the stigma of the task. This is an interesting approach and bares a strong similarity to a publicity event in India over 40 years later. Akshay Kumar, a Bollywood actor and Shri Narendra Singh Tomar, the Union Minister for drinking water and sanitation emptied pit latrines in Madhya Pradesh to end stigma and take pride in installing, maintaining and cleaning their own household toilets for the health of their families" (Hindustan Times, 2017).

A.2 - The impact of poor sanitation on the females of Kumasi

Over two-thirds of those interviewed were female and gender was a reoccurring factor during the interviews. It was evident that a lack of household sanitation was considerably more of an issue for the females of the region. The most heart-breaking reoccurring insight mentioned by several women was their fear of being attacked at night when going to a public toilet. Due to the sensitive nature of this topic and potential for distress this subject further explanation was never sought but as it was mentioned on multiple occasions it is clearly a real concern that many have to live with. In a lighter discussion, a young father described his motivation for getting the Clean Team toilet is a way to stop his daughter from using 'going to the public toilet' as a cover story to go meet boys, jokingly explaining that was what was happening when he was young. It was far more common for the women of the house to initiate the acquisition of the toilet but permission would often be sought from the man of the house. One woman explained with great conviction how she said to her husband she wanted a divorce because their old house didn't have a toilet.

Culture influences household roles and it was normally the job of the woman to clean the toilet and when asked why one respondent answered: "The women always take care of the house and the man doesn't".

Two women mentioned that a Clean Team toilet would make their life easier when pregnant and one woman who was heavily pregnant at the time of being interviewed said it had certainly made her life easier. As the man of the house was rarely there, she had to look after the other young children and not having to worry about walking to the public toilet multiple times throughout the day really helped her. Men being at work or just not being around was not uncommon to hear.

A.3 - Practicalities of Real excreta and simulate

Testing with real faeces is unpleasant to begin with but as noted with sewage workers in a major city (George, 2008), or a pit latrine emptier in an urban slum (Van der Geest, 2007), a degree of tolerance can be acquired. The benefit to testing with real faeces is a true understanding of the real world intended use and the difficulties that will arise from the application.

A.3.1 Practical considerations

Testing with real faeces is fundamental during the development stages but raises a number of challenges. As one gram of human faeces can contain as much as 10,000,000 viruses, 1,000,000 bacteria, 1000 parasite cysts, 100 parasitic eggs (Banerjee et al., 2013) special care has to be taken during collection, handling and disposal. The health and safety risks including contraction of diseases such as Hepatitis, occupational asthma or gastroenteritis meaning appropriate personal protection equipment is required including lab coat, gloves, protective eyewear, face mask and up-to-date relevant vaccinations such as Hepatitis A and B, (Health and Safety Executve, 1991). To reduce this risk a strong disinfectant spray such as Virkon should be used extensively with paper towel on all surfaces and equipment. Disposable leak-proof containers and spatulas reduce risk of contamination and improve efficiency of the testing and ensuring safe disposal in a Biohazards bin is essential. Sterilising equipment under high pressure and heat (121°c) in an autoclave can also be effective when necessary (Pal, 1990). Working in a fume cupboard will reduce the unpleasantness from the odour during testing but isn't always required by laboratory procedure, it can however be good practice not only for the tester's benefit but also others that will have to share the space. Only if faeces is being combusted will a fume cupboard with carbon filtration be mandatory under health and safety procedure (Health and Safety Executive, 2011).

All testing using faeces for this research was approved by Cranfield University Health Research Ethics Committee (CUHREC) under three separate applications. Early volume and user testing were authorized by application 1015 filed by Dr. Peter Cruddas. Authorization for later testing was filed by Ross Tierney and approved under the applications 2883 (surface testing) and 3283 (user testing).

Obtaining and storing of samples also has to be considered. For this project, a rarely used disabled toilet was chosen that would give the participants the time and space to donate a sample making the act as hassle free as possible. Sample boxes were prepared at the start of each day containing gloves, a cardboard bowl for faeces, a bag and sealing ties to seal the sample and reduce smell in the toilet and a bag for waste that will be disposed of in the biohazards bin. At the end of each day the samples are collected and stored in a -80° freezer. To thaw out, they are left overnight in their bags in a suitable location with sufficient labelling. Donations were not always forthcoming and with over 20 people on a mailing list requesting donations there would normally only be around two samples per-day but if a special request for fresh faeces was posted then over ten samples could be collected in one day.

A.3.2 Variations in faeces

Due to collection taken place in a developed country where diet and health will be relatively consistent there is a standard distribution amongst the type of faecal sample obtained with most of the samples being classified as 3, 4 or 5. When testing a range of surfaces multiple faeces would be homogenised to ensure a consistent sample is dropped on each surface.

A.3.3 Simulant faeces

The industry standard media for simulating faeces is soy bean paste, but some companies have their own secret formula (George, 2008). The NASA recipe as it is commonly referred to, was developed for testing new toilets for use in space and is another popular media (Wignarajah et al., 2006). During the surface testing the consistency wasn't found to be relative to real faeces. This was due to the water content of the simulant faeces being much lower than the real faeces holding the same shape. For example, a Bristol stool 4 has a moisture content range of 67%-77% whereas the simulant faeces which had moisture content of 75% shown in figure 14 looked more like a Bristol stool 7. Soy bean paste has been used instead for much of the testing due to its ease of use as it can be ordered in bulk, used straight away without mixing and it's a consist recipe. The moisture content is 50% and its consistency appears to be close to that of a Bristol Stool Chart 4 faece it is also the industry accepted testing material as used in the MaP tests.

Figure 94 - Simulant faeces samples following the sponsor recommended recipe. Sample on the left is 60% solid. Sample on the right is 25% solid.

Figure 95 - Testing the titanium SLIPS surface spin coated with Krytox 105 lubricant using the 75% water simulant faeces

Table 24 - Bristol stool chart for assessing faeces (Radford, Underdown, Velkushanova, Byrne, Smith, Fenner, Pietrovito, & Whitesell, 2015)

Bristol class	IMAGE	Description	Water content
Type 1		Separated hard lumps (hard to pass)	Up to 53%
Type 2		Sausage shaped but lumpy	53% - 60%
Type 3		Like a sausage but with cracks on its surface	60% - 67%
Type 4		Like a sausage or snake, smooth and soft	67% - 77%
Type 5		Soft blobs with clear-cut edges (passed easily)	77% - 85%
Type 6		Fluffy pieces with ragged edges, a mushy stool	85% - 95%
Type 7		Watery, no solid pieces, entirely liquid	Over 95%

A.4 - Original design Brief for RWF from Masters (Tierney, 2014)

Requirements

- No additional water
- No change to user behaviour
- No additional power
- A constant odour barrier

Additional Considerations

- As simple as possible to reduce final cost and risk of failure
- 1.25 litre holding volume for the waste
- As small as possible to reduce overall size required for the toilet
- Adaptability to other systems

Deliverables required

The user interface has to be conveyed to a wide audience at the Reinvent the Toilet Fair in Delhi, March 2014. A full-scale prototype of the toilet has to be produced that gives attendees a complete understanding of the ambitions and direction of the Cranfield entry.

A.5 - Exit point of faeces tests

Each MaP test using both real and simulant faeces was filmed from the side and the landing position of each mass of faeces or soy bean paste was recorded. The axis of the rotating bowl as used as the reference point for each image and Figure 96 shows soy bean paste falling from the rotating bowl and landing below.

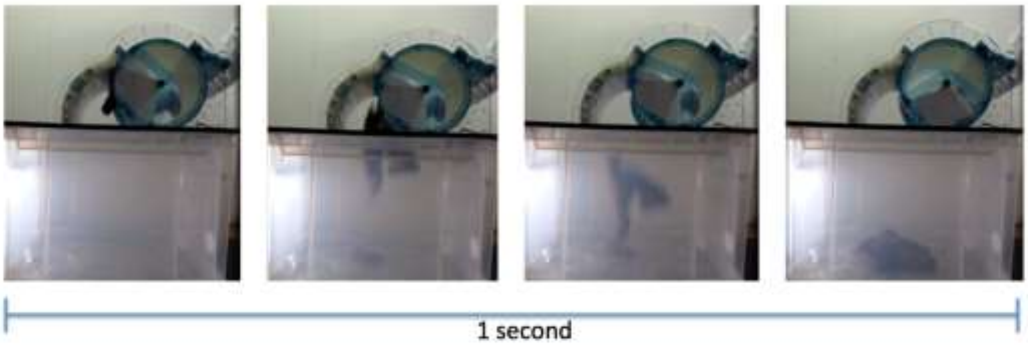


Figure 96- Simulant faeces dropping during the MaP test

Figure 97 shows the combined path of all of the MaP test with soy bean paste by drawing a pink line from each side of the landing area of the faeces to the axis point forming a triangle in a semi-transparent blue. A vertical line is drawn down from the axel of the rotating bowl as the line of 0° and the positioning of the landing is recorded in relation to that line. The darker blue indicates where more of the samples landed. This was to advise the engineering team developing the holding tank where the waste would be expected to land in relation to the bowl.

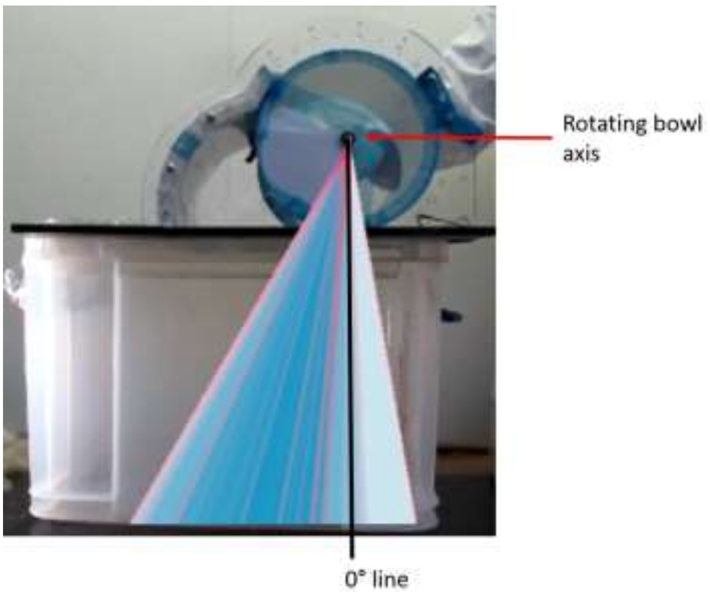


Figure 97 - location of dropped soy bean paste after rotation with most falling before the 0° line.

The accumulated landing positions of both real faeces and soy bean paste are displayed on Figure 98 with the real faeces displayed in Blue and soy bean paste shown in red. There is normal distribution with a range from 16° to -30° and an average of -10° for soy bean paste and a range of 20° to -13° for real faeces.

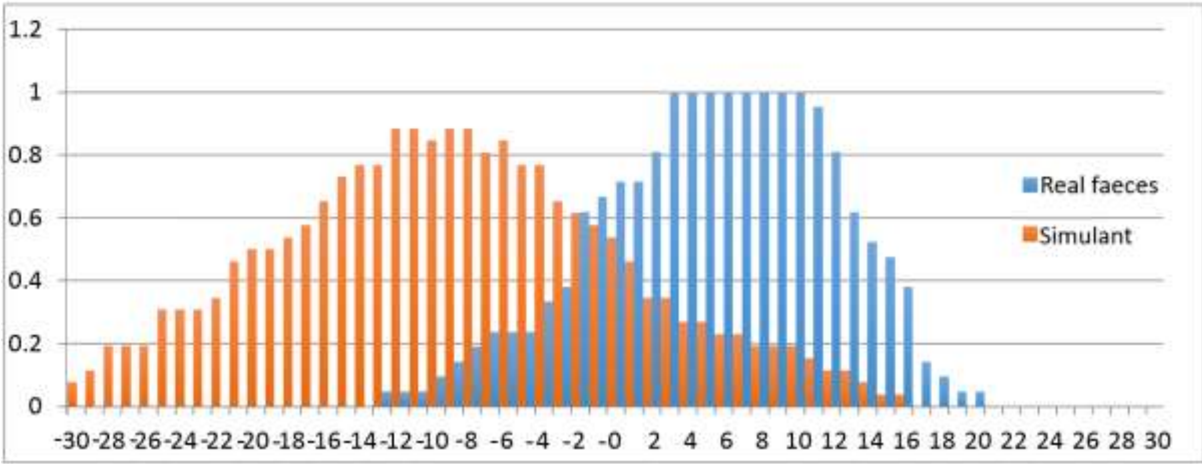


Figure 98 - Graph showing landing location of simulant faeces (soy bean paste) and real feces

There is a clear distinction between soy bean paste and real faeces in trajectory leaving the rotating bowl. To display how this would impact the next part of the system the graph will be reflected horizontally and displayed radially (Figure 99) and with 0' positioned from the axel and projected over a cross section of the complete toilet system shown in Figure 100.

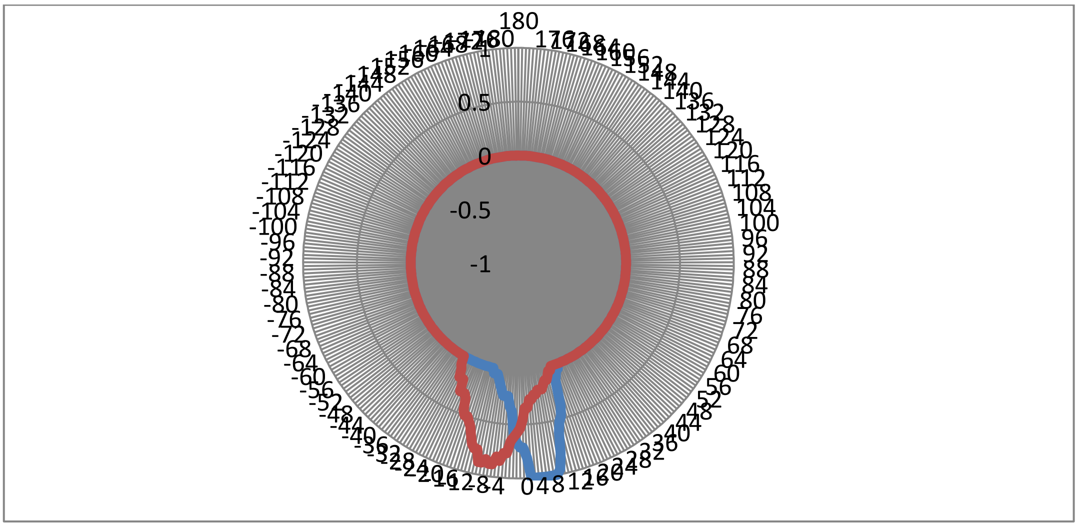


Figure 99 - Radial graph of exit point from rotation with soy bean paste (red) and real faeces (blue)

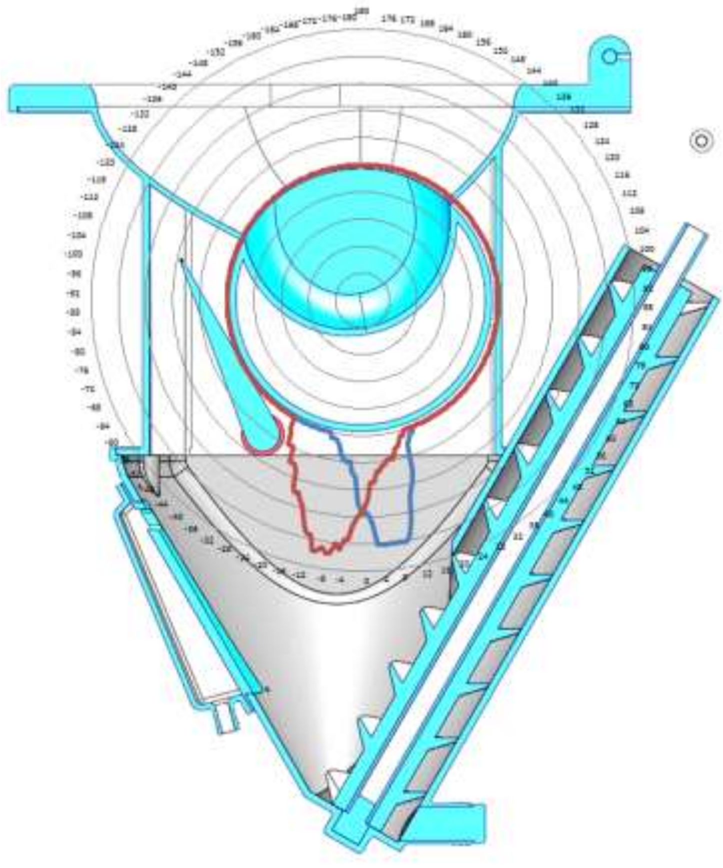


Figure 100 - Radial graph of exit point from rotation with soy bean pate (red) and real faeces (blue) projected a cross section of the toilet system

Real faeces would exit the bowl later that the soy bean paste which was likely due to the consistency and the faeces adhering to the bowl with more strength. This information was presented to the team responsible for the holding tank and Archimedes screw to give a better understanding of how the waste would enter the tank. The exit point of the soybean paste would actually be better for the system than the real faeces as it would land near the bottom of the screw rather than on it however it was also noted that the addition of urine would also have an effect on the exit point.

A.6 - Long-term use

Robust, long-lasting products and components are vital to the improve problems associated with sanitation the developing world. It’s important to understand how repeated use in harsh conditions exposed to excreta will affect performance after many thousands of uses over a products lifecycle. The transport industry is a good example of low-water toilets are used excessively for many years with reliability being highly important. One of the UK’s main train servicing companies; Pneumatic Solutions International (PSI) produced a report for Siemens to assess the failures and causes of the vacuum flush toilets they were supplying them. Each system is used for three years before an overhaul and the units in this inspection had between 28,000 and 42,000 flushes. Overall the number of faults within the system have slowly been increasing each year since their introduction in 2013 with the conclusion being the build-up of Calcite being the cause (PSI, 2016). Calcite is a form of calcium carbonate that forms a hardened mineral scale in toilets due its presence in urine (Ohki et al., 2010).

Figure 101 - Calcite deposit in train toilet after three years and at least 28,000 uses.

A.7 – COSHH for surface testing

Specific COSHH Assessment
CU-HAS-FORM-3.05 (C)
V2.0 APPROVED

Cranfield UNIVERSITY

SPECIFIC COSHH ASSESSMENT

This form is only to be used after completing the COSHH flow chart in Appendix A.

Reference Number:		School/Service:	SEEA	Date of Assessment:	27/3/2017	Next review date:	29/06/2018

Details of Process/Activity Assessed

Building:	Vincent	Location of task:	Vincent	Department/Section:	SEEA
Description of process/ activity/task assessed:	Testing faecal fouling on various surfaces (silicone sheet, ceramic, PTFE, silicone oil)				
Duration and frequency of whole task/process:	27/03/2017 – 27/06/17			Operating conditions:	Routine/ ~~Non-Routine~~

Associated document references:	Risk Assessment Form	Names/type of individuals involved/affected:	PhD students, Technical team and Academics	Does this process pose any significant hazards to the following persons:	Pregnant Workers	Y/N
					Young Workers (<18 yrs)	Y/N
					Disabled Workers	Y/N
				If Yes, individual risk assessment is required	Individuals susceptible to certain illness (e.g. Dermatitis, Asthma, etc.)	Y/N

Actions Required

Is there a corresponding Risk Action Management Plan (RAMP) for this COSHH assessment?	Y/N (delete as appropriate)	If Yes, Reference No:	NA

Acknowledgements, Sign off and Authorisation

	Acknowledgement	Name	Signature	Date
COSHH Assessor:	By signing this risk assessment I acknowledge my responsibility as the COSHH Assessor for conducting this risk assessment in accordance with CU-HAS-PROC-3.05, COSHH Procedure	Ross Tierney		29/3/17.

COSHH Reviewer:	By signing this risk assessment acknowledge my responsibility as the reviewer for this COSHH assessment in accordance with CU-HAS-PROC-3.05, COSHH Procedure			
Authorising Person:	By signing the risk assessment, I acknowledge my responsibility as the department management for reviewing and approving the COSHH assessment and communicating controls and any additional controls to staff/students (as appropriate)	Dr Leon Williams		30-3-2017

A. Substance Information

Include all hazardous substances, by-products, waste materials and cleaning agents.

Substance or Mixture[1] (Chemical / Biological)	Physical Form[2]	Quantities (consider stock and dispensed amount)	Information Source (e.g. SDS, EH40)	Occupational Exposure Limits (Chemical)				Hazardous Properties/ Health Effects/ Special Considerations[6]
				Limit	Units[3]	Ref. period[4]	Status[5]	
Faecal sludge	Solids/Liquids	500g	NA	NA	NA	NA	NA	Harmful to skin, eyes with bacterium and other microorganism pathogens in the sludge and faecal matter
Virkon Disinfectant	Soluble tablet	Solution 1%	SDS	10 4	mg/m^3 mg/m^3	TWA inhalable dust TWA respirable dust	UK EH40 WELS UK EH40 WELS	H272 May intensify fire; oxidiser. H302 Harmful if swallowed. H314 Causes severe skin burns and eye damage. H315 Causes skin irritation. H317 May cause an allergic skin reaction. H318 Causes serious eye damage. H319 Causes serious eye irritation. H330 Fatal if inhaled. H334 May cause allergy or asthma symptoms or breathing difficulties if inhaled. H335 May cause respiratory irritation. H412 Harmful to aquatic life with long lasting effects. R8 Contact with combustible material may cause fire.
Methane in Biogas	Gas	Small	MSDS	1000	ppm	8hour	ACGIH	Inhalation

Carbon Dioxide in Biogas	Gas	Small	MSDS	5000	ppm	None	ACGIH	Inhalation
Sulphur Dioxide in Biogas	Gas	Small	MSDS	15	ppm	15-min	ACGIH	Inhalation-respiratory tract irritation

1. Chemical examples: solvents, oils, lubricants, paints, organic, inorganic compounds, dusts, etc. Include CAS Number and concentrations if known.
   Biological examples: enzyme, human remains, animal remains or tissue, blood, micro-organisms such as bacteria, viruses or fungi – often components of blood, bone, soils, stagnant water. A substance could have both chemical and biological hazards which must be considered.
2. Physical form e.g. solid, powder, crystals, damp solid, liquid, gas, aqueous solution. Include solid particle size if relevant.
3. Units - use parts per million (ppm) or milligrams per cubic metre (mg/m^3).
4. Reference Period: - State 15-min (short-term exposure limit) or 8-hour (long-term exposure limit) or both.
5. Status: - Workplace Exposure Limit (WEL) or relevant limits from other countries (e.g. US Threshold Limit Values (TLV) in the absence of a WEL).
6. For biologicals, record whether there is a certificate of screening and deemed free of pathogens. Include any associated hazard class for the material.
   For chemicals, record all of the associated H statements/R phrases e.g. H331 Toxic if inhaled/R23 Toxic by inhalation. See Appendix F of the COSHH procedure.

For Carcinogens, Mutagens, Reproductive Hazards, Sensitisers/Asthmagens, Teratogens, Nanomaterials or when hazards are unknown, send the assessment to your Local H&S lead or the University Health and Safety Unit for review. Health Surveillance may be required. Contact Cranfield University Occupational Health for information.

B. Prevention of Exposure

Can you eliminate or substitute any aspect of the process or any hazardous material for less hazardous? Justify the safe use of chosen substance(s).

No. The tests are required as a developmental measure for performance assessment of the Nanomembrane Toilet project. PPE including eye protection, filter mask, gloves, lab coat/boiler suit.

C. Exposure Assessment

Include all potential sources of exposure

Operation/Activity (Describe the major stages/steps of the process/activity)	Substance(s) Present (List substances present or released at this step)	Approx. amount used at this step (e.g. g, kg, litres)	Exposure Route (inhaled, skin absorption, ingestion, inoculation etc.)	Frequency of operation (per day/shift)	Total activity duration (mins)	Controls used for this step[7]	Existing Risk Rating Severity of potential harm x Likelihood of exposure = Total [1-5] S[8]	L[9]	TAL[10]	Are additional controls needed? Y/N[11] (If Yes, RAMP required)
Cleaning rig	Virkon disinfectant Stable when in solution	500ml , 1% solution	Skin, Eye Absorption , Ingestion	Per day	60	Ensure no dust from tablet is created when preparing solution. Prepare into spray bottle to prevent spillage. Wear general lab PPE.	2	2	4	N
Faecal & Sludge disposal	Methane, Hydrogen Sulphide, Sludge & Wastewater	500g solids	Skin, Eye Absorption , Ingestion	Per day	60	Written procedures. General ventilation, PPE, Vaccination.	2	2	4	N

CU-HAS-FORM-3.05 (C) Page 3 of 5 V2.0 25/04/14

Comments:

7. List the specific controls already in place. Use the hierarchy of controls: Elimination, Reduction, Engineering Controls (isolate/prevent contact), Administrative Controls (SOPs), Housekeeping, Personal Protective Equipment (PPE). See Appendix J control requirements for Carcinogens and Mutagens. See Appendix K for control requirements for Biological Agents. See HSG272 for Nanomaterials.
8. See Appendix G for severity definitions and scoring. Severity should be based on information including the worst case illness.
9. See Appendix G for likelihood definitions and scoring. Likelihood should be based on how likely ill health is to occur. Good existing controls will reduce the likelihood.
10. The total existing risk rating is determined by Severity x Likelihood. See Appendix H.
11. If additional controls are required the Risk Assessment Management Plan (RAMP) in Appendix D must be completed in conjunction with the Assessor, Authorising Person and Responsible Manager. Once actions in the RAMP are complete, update the COSHH assessment and recalculate the risk rating.

D. Incident, Accident or Emergency Procedures

Focus on the substances that need special treatment in the event of a spillage, uncontrolled release, or other emergency

What might go wrong?	Describe the type of incident that may happen with these substances (Potential spillage/release volume, locations affected)	Increase above acceptable levels of methane and Hydrogen Sulphide in the air within 244. Wastewater spillage.
First Aid	Describe any special First Aid treatment required when dealing with a person exposed to substances assessed	If inhaled – move to fresh air, open the door/windows in 244 If skin contact – rinse off with soap and water, emergency shower If eye contact – rinse with water and emergency eyebath If swallowed or contact with mouth – rinse with water
	Describe any adverse (non-immediate) health effects that may occur after exposure to substances assessed	Respiratory, eye irritation, skin irritation
Spillage	State locations of SDS, COSHH assessment and spill kits	SDS and COSHH assessment are 244. Spill kits located near chemical store room.
	Is the spill kit and associated equipment suitable for the substances to be used? If not, suitable equipment must be obtained and instruction given before starting work.	Use spill kits to contain and collect spillage and store for disposal to the proper container.

CU-HAS-FORM-3.05 (C) Page 4 of 5 V2.0 25/04/14

Fire/Explosion	Describe any special precautions required in the event of a fire or other emergency	Methane and Hydrogen Sulphide are extremely flammable in case of leak, ring security (2222) and evacuate 244
Environmental	Do the substances used pose a threat to the environment? (land, air, water – open drains, surface water). If yes, complete an Environmental Risk Assessment CU-EMF-009	No. Disinfectant will be used in small quantities with paper towels.

E. Occupational Hygiene Monitoring and Health Surveillance Requirements				
	Required (Y/N)	Frequency	Consultation outcome (Who was consulted & Comments)	Job Title
Exposure Monitoring – Biological monitoring, Toxic substance monitoring (consult the University H&S Unit as necessary)	N			
Health Surveillance (consult the University Occupational Health department)	N			

F. Waste Disposal			
Is hazardous waste generated requiring disposal?[12]	Y/N	If Yes, give details of relevant disposal methods	NA

12. Refer to your local arrangements and the management of laboratory waste procedure CU-ENV-3.05

G. Information, Instruction and Training - requirements for staff/students working on this process	
Information which needs to be communicated on the findings of this assessment	Categories of personnel to be informed
Wear standard PPE and do not inhale dust	
Additional Supervision, Instruction, Training and Monitoring Checks Requirements	Categories of personnel to be trained

A.8 - RWF patent

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

WIPO | PCT

(43) International Publication Date
8 September 2017 (08.09.2017)

(10) International Publication Number
WO 2017/149036 A1

(51) International Patent Classification:
E03D 11/10 (2006.01) *E03D 11/12* (2006.01)
A47K 11/02 (2006.01)

(21) International Application Number: PCT/EP2017/054820

(22) International Filing Date: 1 March 2017 (01.03.2017)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
1603551.1 1 March 2016 (01.03.2016) GB

(71) Applicant: CRANFIELD UNIVERSITY [GB/GB]; Cranfield Bedfordshire MK43 0AL (GB).

(72) Inventors: WILLIAMS, Leon Brett Matthew; C4D, Building 82, Cranfield University, Cranfield Bedfordshire MK43 0AL (GB). LARSSON, Jake Aaron; C4D, Building 82, Cranfield University, Cranfield Bedfordshire MK43 0AL (GB). TIERNEY, Ross Cochrane; C4D, Buidling 82, Cranfield University, Cranfield Bedfordshire MK43 0AL (GB). COLLINS, Matthew Spencer; C4D, Building 82, Cranfield University, Cranfield Bedfordshire MK43 0AL (GB).

(74) Agents: NAYLOR, Matthew et al.; Mewburn Ellis LLP, City Tower, 40 Basinghall Street, London Greater London EC2V 5DE (GB).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

[Continued on next page]

(54) Title: TOILET AND OPERATION THEREOF

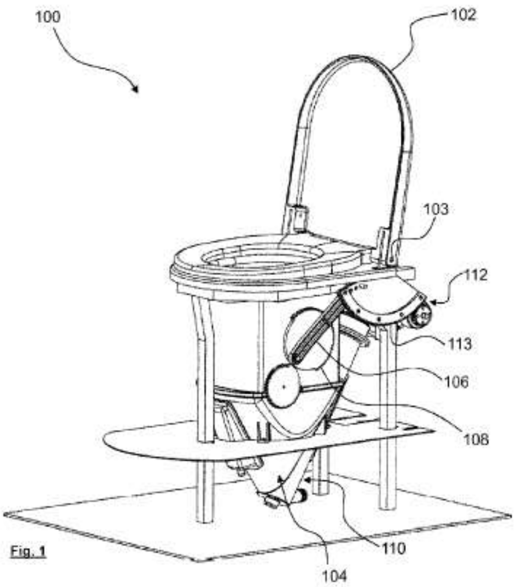


Fig. 1

(57) Abstract: A toilet is disclosed, having a bowl (400) for receiving human waste and a wiper (402). The bowl (400) is moveable between a waste receiving position and a waste emptied position. This movement is provided based on a waste emptying actuation by a user of the toilet. The wiper (402) is movable to remove residual waste from an inside surface of the bowl (400) by wiping the inside surface of the bowl (400). The movement of the wiper (402) is coupled to the movement of the bowl (400), the wiper (402) being configured to move during the movement of the bowl (400), for at least a part of the movement of the bowl (400) between the waste receiving position and the waste emptied position.

WO 2017/149036 A1

A.9 Secondary target market questionnaire

Toilet survey

A) What are the five most **frustrating** aspects of using dry toilets?

1. ....
2. ....
3. ....
4. ....
5. ....

B) What are the five most **pleasing** aspects of using dry toilets?

1. ....
2. ....
3. ....
4. ....
5. ....

C) Our research in Ghana identified the following factors to be important performance indicators for the toilets in the area. Can you mark on the scale below how much you agree or disagree with the following statements?

Performance indicators	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Dry toilets have no odour from collected waste					
Dry toilets are easy to use by less-abled people					
Dry toilets have no sight of other people's faeces or toilet paper					
Dry toilets are easy to clean					

1.

See rotating bowl

D) By taking your five answers from question A (regarding the frustrations of a dry toilet) can you mark with an 'X' how much you would agree that the new technology alleviates each of these frustrations?

Frustration	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Answer 1					
Answer 2					
Answer 3					
Answer 4					
Answer 5					

E) From your first impressions of the rotating bowl, how much do you agree with the following statements:

Performance indicators	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
The new rotating bowl will reduce odour from stored waste					
The new rotating bowl will be easy to use by less-abled people					
The new rotating bowl will prevent sight of other people's faeces or toilet paper					
The new rotating bowl will be easy to clean					

2.

F) From your first impressions of the rotating bowl, how much do you agree with the following statements:

Statements	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
This rotating bowl is an improvement to standard Dry toilets					
This rotating bowl would be compatible with current behaviour of the toilet user.					
This rotating bowl would be a simple technology for the user					
It would be possible to trial this rotating bowl with our current system.					
The benefits of the rotating bowl would be clear for all users					

3.

A.10 Testing odour neutralisation

The toilet is a typical source of offensive odours in everyday life (Sato et al., 2002). Faeces is considered the most unpleasant of odours to humans and a prominent stimulus for disgust and repulsion (Afful, Oduro-Kwarteng and Awuah, 2015). The belief of faecal odour causing contamination of the air and disease has existed since ancient times and is a reason some people still prefer to openly defecate rather than use a latrine (Rheinlander et al., 2013). Toilet users can employ a combination of methods to prevent, reduce or combat smells and improve the experience (Hermans, Rimé and Mesquita, 2013). Extraction systems can direct malodorous air outside, air fresheners in a variety of forms (aerosol, liquid perfume and solid media) can either mask the smell by binding with volatile organic compounds (VOC) or overpowering them with an alternative pleasant smell (Seo and Seouk Park, 2013). A more complex method of odour neutralizing is by using triatomic oxygen (O_3) commonly referred to as ozone. Ozone is a powerful disinfectant that destroys organic compounds or bacteria by oxidation neutralizing virtually all organic odours (Pekarek, 2003).

Sato *et. al* (2002) conducted an analysis of malodourous substances of human faeces using thermal-desorption cold-trap injector gas chromatography/mass spectrometry (TCT/GC/MS). TCT/GC/MS explains the processes involved from capturing the VOCs then separation and identification. Thermal desorption captures and concentrates compounds to be analysed once injected into a GC/MS. Gas Chromatography uses an inert gas phase to separate different components, then mass spectrometry measures mass-to-charge ratios of the fragmented compounds for comparison against a database library of known compounds (Mae et al., 2016). The malodorous compounds of faeces are profiled in Table 25 and are supported by earlier work in the area (Moore, Jessop and Osborne, 1987).

Table 25 - Concentrations of malodorous compounds in human faeces (Sato et al., 2002)

	Compound	Concentration (ppb)
Sulfur-containing compounds *b)*	Hydrogen sulfide	5-26
	Methyl mercaptan	2-15
	Methyl sulfide	nd[a)]
	Dimethyl disulfide	nd[a)]
Nitrogen-containing compounds *b)*	Trimethylamine	0.01
	Ammonia	<100
Aldehydes *b)*	Formaldehyde	nd[a)]
	Acetaldehyde	nd[a)]
	Propylaldehyde	10
Fatty acids *c)*	Acetic acid	3-10
	Propionic acid	2-11
	Butyric acid	<0.4
	iso-Valeric acid	<0.1
	n-Valeric acid	<0.1
Others *b)*	Pyridine	0.03-0.23
	Pyrrole	0.01-0.02

a) Not detected. *b*) Concentration of compounds under normal conditions and diarrhea. *c*) Concentration of fatty acid under normal conditions

Two different experiments were conducted to investigate whether ozone could be used to neutralize the odour of faeces however both experiments were declared as failures. The first experiment used two clear plastic sealing boxes with equal amounts of a homogenized faeces sample inside each of them. A port on one side of the box allowed for a thermal desorption tube to be attached with a pump drawing the air from inside the box through the TD tube. A hole on the other side of the box allowed for air to enter into the box and equalize the vacuum caused by the pump. In the first box was an AirLife odour neutarlising system and in the other was a foam block that replicated the volume of the AirLife system. It was expected that the GC/MS would identify some or all of the compounds associated with the odour of faeces shown in Table 25 in the first box and a reduction or removal of the compounds in the box that has the AirLife system. The results were irregular with only two of the compounds Acetic acid and Acetaldehyde identified

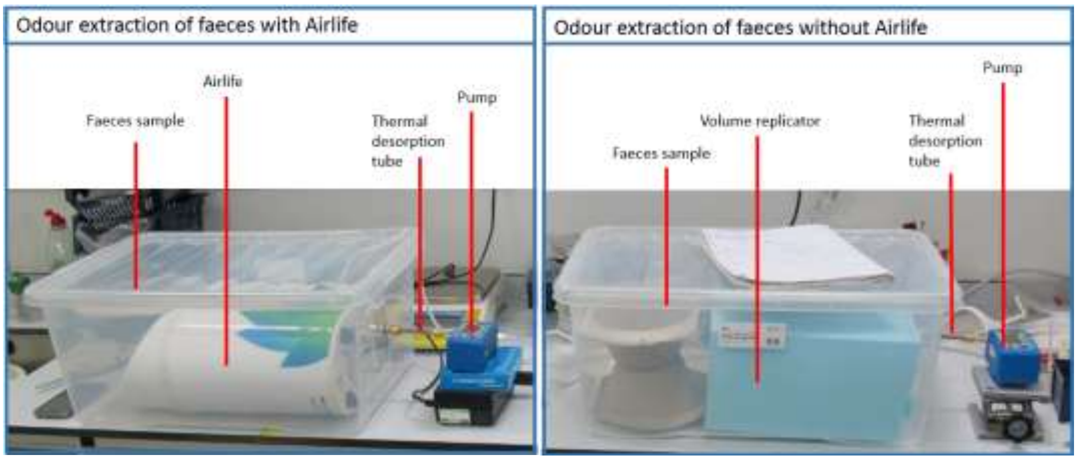


Figure 102 - Faeces VOC testing

Testing odour proved to be more difficult than expected with key components expected to be present on the results of the GCMS missing from the data. Two experts in the field of odour detection and testing were involved during the process and both were perplexed as to why the key compounds were not present. The availability of the GCMS limited the research in this case as there was a long period between conducting the test and receiving data for both sets of test