CRANFIELD UNIVERSITY

Connor Hart

# Comparative evaluation of competing technologies through rapid prototyping

School of Water, Energy and Environment (SWEE)

MSc by Research
Academic Year: 2017- 2018

Supervisor: Dr Matt Collins
Associate Supervisor: Professor Peter Jarvis
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# ABSTRACT

A major difficulty often experienced by multidisciplinary teams, particularly between scientific and design led approaches, is how to resolve the conflict which arises between competing ideas, in order to facilitate the most efficient path towards a successful technological innovation.

This project has attempted to demonstrate the vital role which agile innovation, made possible only through rapid prototyping, can optimise two competing technologies in-order that they can be tested and evaluated across a spectrum of qualitative and quantitative parameters. The results of which can enable the wider project team to select the correct path forward.

A systematic review of literature revealed that design literature in this space is limited, with few real-world case studies conducted in this area. This research provides a valuable practical case study which shows agile innovation in action and the critical role which rapid prototype plays in that process.

A multi-category matrix was newly created, providing metrics for both qualitative and quantitative data, and which uses a colour-coded scoring system to give a detailed and overall rating for each technology.

The findings were controversial, but unequivocal, and could have a major impact on the development of the wider project going forward.



**Keywords:**

Agile innovation, Rapid prototyping, Technology evaluation, Metrics

# ACKNOWLEDGEMENTS

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| | |
|---|---|
| BMGF | Bill and Melinda Gates Foundation |
| PSPU | Peristaltic Pump Unit |
| CAD | Computer Aided Design |
| CAM | Computer Aided Manufacture |
| 3D | Three Dimensional |
| RP | Rapid Prototyping |
| AM | Additive Manufacturing |
| SM | Subtractive Manufacturing |
| FDM | Fused Deposition Modelling |
| FFF | Fused Filament Fabrication |
| SLA | Stereo Lithography Apparatus |
| SLS | Selective Laser Sintering |
| ABS | Acrylonitrile Butadiene Styrene |
| Nylon | Aliphatic Polyamides |
| ER | Experimental Rig |

# 1 Introduction

The Bill and Melinda Gates Foundation set a challenge to a select group of universities and institutions worldwide, to Reinvent the Toilet. The aim of which is to provide proper sanitation solution to third world areas such as South Africa. Cranfield University was one of the selected institutions to take on this challenge and so the Nano Membrane Toilet was proposed. With the idea of treating human waste onsite without the use of external energy or water. So, in 2012 work began developing and inventing this revolutionary toilet. To allow multiple teams from different disciplines within Cranfield University to work on the overall Nano membrane toilet design, it has been divided into two sections (see figure 1). The front end, which encompasses everything that is visible to the user, everything the user will interact with, as well as the section that the waste is contained within and transported from. The back-end is everything that is used to processes the waste material from the front-end, resulting in clean and safe by-products such as water and ash. For the research conducted will be on the front end of the toilet, with the focus being on the transportation of the waste material from the front-end to the back-end.

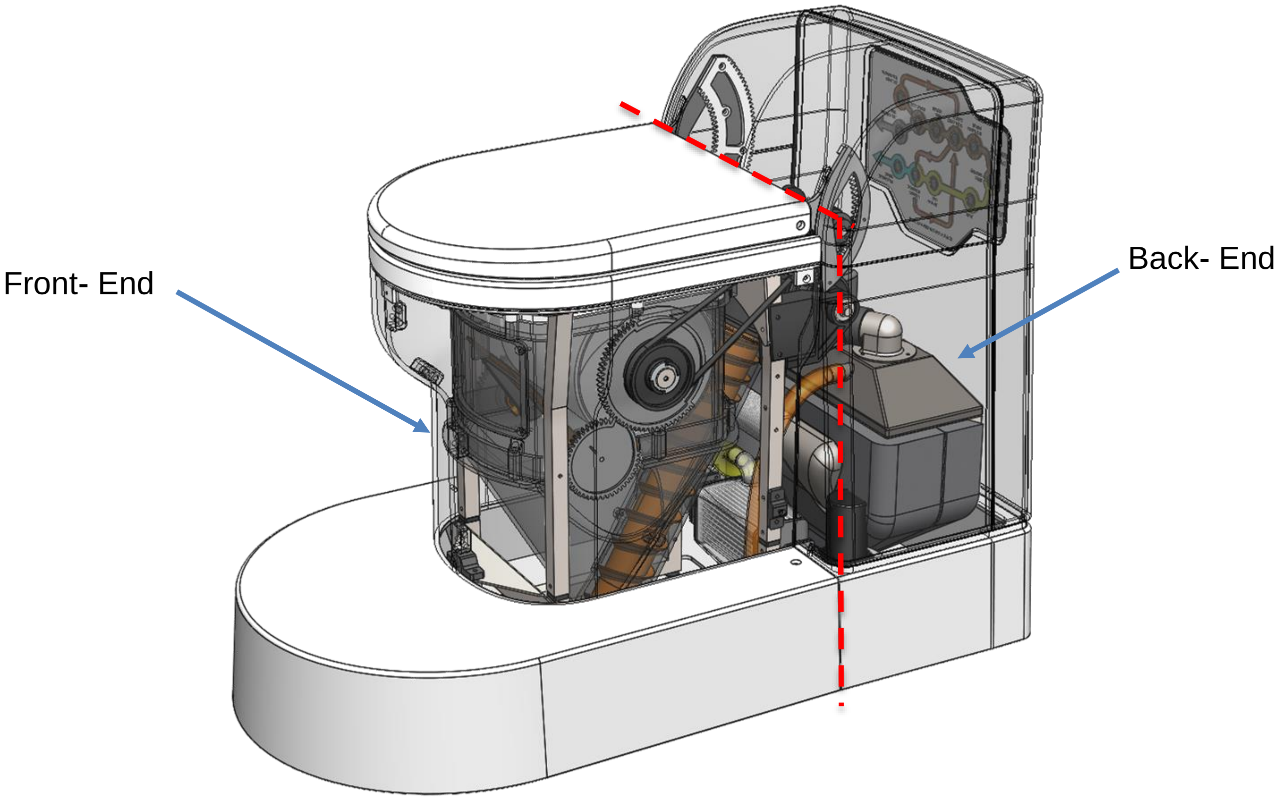


**Figure 1.** *Cranfield Nano membrane toilet HUT2.5 Front-end/Back-end*

The reason for this research being conducted is due to an ongoing concern regarding transportation of the waste from the front-end to the back-end. Currently the design known as the Nano membrane toilet, uses an Archimedes screw to lift the solid waste from the settling tank to the top of what will be a dryer unit. An issue that has been observed both on the current prototype (see figure 2) and on the previous version. Is that the screw isn't purging the settling tank as it should, nor is any dewatering taking place. If the screw is unable to purge the settling tank of the solids, it will lead to the tank overfilling and the back-end not receive any waste to process make the components of that system inoperable. At the current point in the project, near the end of phase three, the front-end design is becoming refined. Nearly to the point where large changes such as removing the screw for an alternative, would require large change be made to the design to incorporate the new solution.

**Figure 2.** *Cranfield Nano membrane toilet HUT2.5 Front-end*

However, an alternative solution has been in development alongside the current screw version of the toilet, the Peristaltic pump unit (see figure 3). The peristaltic pump front-end version is directly driven from the closing of the lid, so it is design to pump waste from the bottom of the tank after each use. This waste is pumped to a settling tank which unlike the screw version doesn't require settling to occur before transportation, instead allows it to occur after it. Currently the peristaltic pump version shares many of the same main components used in the screw version, making a possible integration to the design far easier at this stage.

**Figure 3.** *Cranfield Nano membrane toilet Peristaltic Pump Front-end*

This uncertainty as to whether the current screw version is the optimal solution has meant the need for a head to head to test between the screw version and peristaltic version to be conducted. The results from the test will then be used to generate a matrix system which will give values to important pieces of information, to aid in further development in the Nano membrane toilet. It will also allow for a decision to be made as to which should be developed further into the full system prototype.

To understand the theory behind what prototyping is and how it is defined. A literature review is carried out looking at prototyping and how it is defined within design, how it can be used to test concepts and what effect it has on the overall design of a product. Furthermore, looking at the possible negative side effects of prototyping, possible design fixation which could have a detrimental effect on the outputted concepts.

# 2 Literature Review

## 2.1 Literature review of design fixation and prototyping:

The following literature review looks into how prototyping is defined within design. It follows on by identifying what design fixation is and its effects on overall design creativity. Further expanding upon this it finally investigates the use of prototypes and whether the use of the will lead to design fixation. The final section of this review looks at design method, what it is and gives different examples of design methods that can be used.

### Prototyping

***Prototyping*** can be defined as the process of generating an experimental model used as a representation of a design concept. Prototypes are an important asset in the product design and development process. Using them to simulate a design can reduce the design risk due to not committing to the time and cost involved with a full production run (Houde and Hill, 1997). They are the embodiment of a design concept, ranging from 2D drawings that represent a designer's thinking (Suwa and Tversky, 1997) or a simple foam model mock-up of a design, to incredibly sophisticated 3D models created using rapid prototyping technologies, which are almost indistinguishable from an actual full production design. Prototypes by definition are not production stage designs (Yang and Epstein 2005). They constitute instead the systematic development of a design concept in order to test feasibility and to enhance details within the pre-production design (Badri, 1997).

Using prototyping to evaluate a design concept, allows questions to be formed about the overall design or specific areas within it, which will consequently be answered by testing the prototype. Such questions can be 'does the design perform as expected?' or 'are there any assembly or tolerance issues?' In addition, prototypes are an effective way to compare design variants and aid in the overall concept selection process. Ward et al. (1995) explore the practice of constructing a large number of prototypes in order to explore the different design variants before selecting the final one. This contradicts a belief that some say is common wisdom in design, which is to go into deep exploration of a design in the conceptual stage before any fabrication begins (Yang and Epstein, 2005).

Prototypes are not only a way for the designer to gain a practical insight into their design, but also a way of communication (Kolodner and Wills, 1996; Schrage and Peters, 1999). They are a tangible, visual representation of a concept which provides a view, able to be shared with all those involved in the design process. Furthermore, the actual building of the physical prototype can show up issues such as holes that are inaccessible or interference between parts. These issues are sometimes hard to identify using other representations of the concept (Yang and Epstein, 2005). The process of designing the 2D initial development drawings and then the development of a 3D CAD model provides a wealth of information about the design concept. But this information will likely differ from the information gathered about the design from the actual construction of a prototype. This means prototypes can be categorised by their term of purpose or the question that they aid to answer. Ullman (2003) breaks prototyping down into four categories. These allow prototypes to be given a class based upon their function and the stage at which they are used in the product development cycle. They are as follows:

1. *Proof-of Concept:* These are used to give a better understanding as to the approach to take in the initial stage of the design.
2. *Proof-of Product:* Used to evaluate a designs physical embodiment and to measure is production feasibility.
3. *Proof-of Process:* Shows that the production methods and materials used result in the desired end product.
4. *Proof-of Production:* Finally, these are used to demonstrate that the whole manufacturing and production process is working effectively.

Following on from this classification of prototypes, Houde and Hill (1997) go on to further breakdown what makes a proof-of concept prototype. They created a triangle model as seen in Figure 1, which breaks proof-of concept down into 3 main purposes.

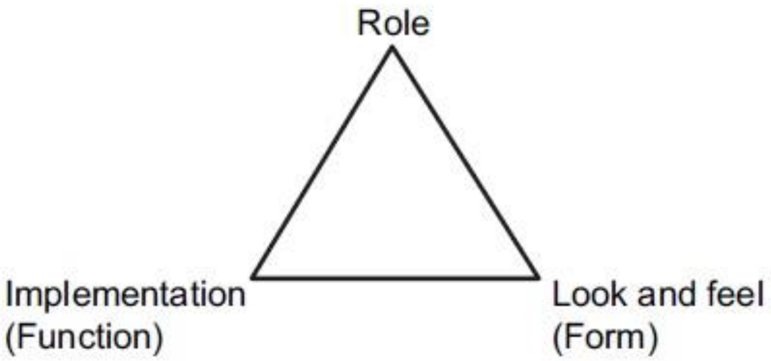


**Figure 4.** *Early stage proof-of concept purpose triangle.*

- *Function*: the design's ability to operate in the way it is intended. Looking from a mechanical point of view, a working prototype demonstrates the functionality of the design.
- *Form*: this can be represented using a *look-and-feel* prototype. Its sole purpose is to portray the aesthetics of the design and it is non-functional. These are commonly used by industrial designers who normally use foam or generate a rendered 3D model of the design.
- *Role*: this is usually demonstrated using story boards to give a sense of usability for the user, looking at how the product will be used.

### Design Fixation

Blind adherence to a set of concepts or ideas will inevitably lead to the limiting of the outputted conceptual designs (Jansson and Smith, 1991). The idea of design fixation was first discussed by gestalt psychologists (Duncker, 1935/1945; Scheerer, 1963). ***Design fixation*** refers to the phenomenon where a designer fixates there thinking on an example or a previously developed solution, which is not related the problem in its current context. According to a hypothesis by Jansson and Smith (1991), design fixation is a measurable barrier. Its notion seems to go against the idea that using existing examples during the idea generation stage is supposed to aid ideas.

The design fixation theory is supported by a number of research studies that have been carried out (Cardoso and Badke-schaub, 2011). Smith et al. (1993) carried out a test consisted of participants who were asked to create creatures that would inhabit another planet (Smith et al., 1993). Some participants were shown some examples related to the experimenter set topic prior to generating their original ideas. Those who had viewed the examples had a significant tendency to conform to the examples, in some cases reproducing them. These findings are like those of a similar test conducted by Smith and Blankenship (1991). Similar results have also been seen in subsequent studies considering creative cognition to solve tasks (Ward, 1991). The test conducted by Cardoso and Badke-schaub (2011) followed the same trend showing that participants exposed to picture of current ideas generated, resulted in higher repletion of key attributes of the original. The authors also went on to create a diagrammatic representation which shows the possible outcomes of the idea generation process (Figure 2).

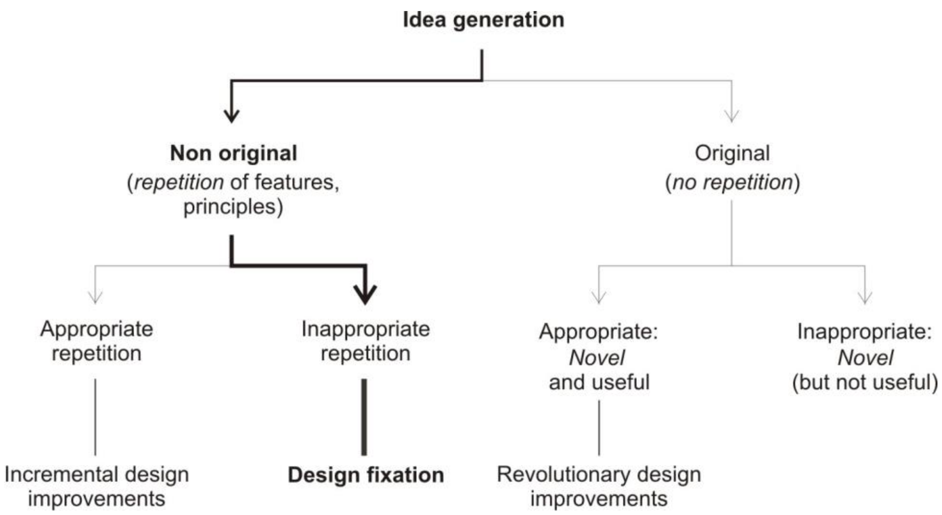


**Figure 5.** *Possible outcomes of an idea generation process (Source:* Cardoso and Badke-schaub, 2011*).*

The diagram shows that design fixation does not mean that repeating features of an existing design always leads to design fixation. Only when there is an inappropriate amount of repetition will design fixation occur. This leads to the following questions: 'how do we know when the repletion is appropriate?' and 'can the disciplinary background someone comes from impact on design fixation?' Purcell and Gero (1996) considered this comparing industrial designers with mechanical engineers. The conclusion was that design fixation could be related to educational programmes due to the constant following of set ways of designing. However, ~~the~~ industrial designers are trained to be thinking of novel ideas generating new designs, meaning they show less design fixation in their generated solutions. On the other hand, research conducted by Marsh and colleagues (1999) found that the examples given to subjects where not consciously causing them to generate solutions similar to those seen in the examples. It instead found that subconsciously the participants where constraining themselves. Marsh, Ward and Landau (1999) demonstrated this by conducted a similar test to Smith, Ward and Schumacher (1993). But instead of showing some participants the examples, they showed examples to all of them. They then informed some of the participants not to recreate the examples they have been shown. The similarity of the generated solution and the example did not show any significant decrease between those participants informed not to copy the example and the ones who were not. The results from this test would suggest that a designer is unaware that they are using prior knowledge or that they are being influenced by examples for the solution to a problem (Linsey et al., 2010). Lindsay, Wood and Markmen (2008) previously observed a similar phenomenon in engineers who, similar to designers, where unware they were using prior examples they had been exposed to.

**Does design fixation occur when prototyping?**

As observed by Ulrich and Eppinger (2013), prototyping can fall anywhere between being fully physical or fully virtual. Römer et al. (2001) suggest that the generation of physical models during the early stages of the design process reduces the cognitive load experienced by the designer. This is due to them being able to externalise their ideas. Physical models aid designers by allowing them to visualise and solve problems that involve complex systems (McKim, 1972). They also allow designers to identify flaws in their designs, which in turn leads them to create more feasible designs (Viswanathan and Linsey, 2012). It is because of these advantages that most, if not all, product design firms strongly encourage the use of physical prototypes in the early stages of design (Ward et al. 1995; Kelley and Littman, 2001). This encouragement gives the impression that there is a benefit to the use of prototype. However, Kiriyama and Yamamoto

(1998) observed that student design teams tend to fixate on their initial design ideas while using physical models to solve the problem. This idea that novice or student designers fixate is contradicted by Youmans (2011) who showed that novice designers actually fixate less, during the idea generation phase if they use physical prototypes.

The use of prototyping early in the design process correlates with better design performance (Yang and Epstein, 2005). This is further backed up by Jang and Schunn (2012) who, by conducting an experiment, determined that a successful design team uses prototypes throughout the design process and not only to represent concepts, but to also to communicate ideas. They go on to further state that restriction on prototyping will inevitably lead to design fixation, regardless of any technical faults that may exist within the concept. The notion that technical faults have no effect on design fixation reinforces the idea that we learn from our mistakes. From a cognitive point of view, Franck and Rosen (2000) suggests that the use of low fidelity prototypes, which are incomplete containing some main features but are otherwise simple, benefit the design team in 3 main ways.

1. *Failure is reframed as an opportunity for learning.*
2. *A sense of forward progress is fostered.*
3. *Beliefs about creative ability are strengthened.*

So, although it has been observed that design fixation can occur when using prototypes, it is more widely agreed that prototypes are a valuable resource and should be used as a way of preventing design fixation from limiting the overall outputted concepts.

**Design Method:**

***Design method*** is defined as a system of methodical rules and instructions intended to guide the execution of a certain design activity (Eder & Hosnedl, 2007). Each method can be divided into more basic methods or to be combined with others into more comprehensive ones. A set of methods is called ***design methodology***. Thus, this term covers different sets of design methods corresponding to various fields of activities or branches of specialisation.

Although a complete catalogue of design methods is almost impossible to be presented, as there are always revised and revisited methods appearing in the literature, Table 1 summarises the most common methods, each one corresponding to a distinct stage of the design process (Note: in the following table TS stands for Technical Systems and TP for Technical Process).

**Table 1.** *Literature of different Design methods*

| **Title** | **Description** | **Goal** |
|---|---|---|
| Abstraction | Derive a more abstract form of representation of a problem or system from a concrete form, for example, formulate TS-functions from an existing layout | Open a solution field to search for alternatives in more concrete representations |
| Adaptation | Modify or partially transform an existing TP and TS for different conditions | Obtain a reliable solution for new conditions |
| Aggregation | Combine TP and TS subsystems into a single system, or combine functions of several organs into one function or organ | Achieve new properties, simplified structure |
| Alexander's component method | Identify contributing components to a complex design problem | Allow suitable sequencing of design considerations and decisions |
| Analyse Theorize Delineate Modify | Recommend a problem-solving sequence with forced iteration | Historic formulation of a theory of design |
| Analysis of Interconnected Decision Areas (AIDA) | Identify components of a problem and their relationships | Grouping of components of the problem to reduce influences of relationships |

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| Analysis of Properties (Attribute Listing) | Analyse every TS-property, list all attributes (properties, characteristics) of the thing to be designed, consider each separately to decide whether any can be usefully changed | Improvement of an existing TS |
| Analysis of Variance (ANOVA) | Mathematical statistical treatment of experimental data to discover influences of environment properties on the behaviour of a system | Identify those properties that have the greatest effect on behaviour |
| Art Gallery Method | Display several concepts or layouts with alternative solution proposals, discuss advantages and disadvantages of competing layouts by viewing the displays in a team situation | Select and synthesise the most favourable constructional structure from several proposals |
| Axiomatic Design | Use simple axiomatic statements to guide selection among proposed alternative solutions | Apply linear matrix algebra to decision making |
| Benchmarking | Provide comparisons among competitors about products and organizational procedures and structures | Improve own products and organizational procedures and structures |
| Black box | Define inputs and outputs of a process, and its transformation | Observe and modify the transformation in isolation, independent of the |

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| | | mechanisms that cause the transformation |
| Blockbusting | Overcome mental blocks and prejudices by freeing the mind | Improve search for solutions by avoiding fixation on existing solutions |
| Boundary Element Method | Approximate iterative computer solution of systems of equations with assumed boundary conditions, by dividing a continuous geometric boundary into discrete elements, to model physical phenomena | Find a close analogy to the behaviour of a physical phenomenon |
| Boundary search/shifting | Investigate effects of redefining the boundaries of the system | Find better distribution of tasks among systems and operators |
| Brainstorming | Collect ideas in free discussion without criticism | Find many solutions to a given problem |
| Cause and effects analysis | Analyse consequences (“effects”) attributed to causes (causally or statistically) | Clarify relationships |
| Check lists | Use suitable lists of items as guideline for considerations | Completeness of task |
| Computer-aided design/drafting (CAD), computer-aided engineering (CAE), and computer-aided manufacture (CAD/CAM) | Using a computer to represent a TP and TS being designed (CAD), perform suitable analyses to assist designing (CAE), and convert data about | Capture the “design intent” for a designed product (geometry, tolerancing, all considerations toward design properties) for retrieval and modification |

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| | constructional parts for CAD/CAM | |
| Computer Integrated Manufacturing (CIM) | Computer control of manufacturing plant and inventory | Management supervision |
| Concept map | Show a set of concepts, and by labelled links describe their relationships, as a hierarchical or network representation | Present a graphical image of related concepts to improve Understanding of a situation |
| Concept Selection | Pair-wise comparisons of proposed solutions according to selected criteria, performed in teams | Select an optimal solution among given proposals, and improve it |
| Concurrent engineering | Perform design work on the product and the manufacturing process at the same time | Best trade-off between design features and manufacturing cost/difficulty |
| Continuous improvement | Search for ways to improve the operation of the organization or its sections | Many small improvements over a period of time can result in a large change |
| Cost-Benefit Analysis | By analysing costs and benefits in monetary terms, select a solution among the proposals | Find an optimally economic solution |
| Critical Path Network/Planning/Method | Graphically represent the envisaged activities and their duration | Create an overview of sequence and timing and find the critical path, shorten times |

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| Decision Tree | Keep records of decisions about a TP/TS, as a hierarchical tree | Allow retracing of decision steps |
| Design catalogue | Collected and categorised information about possible solution principles to fulfil a function, including mathematical relationships | Present information to assist creative search for modes of action |
| Design for properties and life cycle | Collect information about favourable principles, forms, and arrangements that will optimize the system to be designed for each property (cost, functional integration or separation, assembly and disassembly, testing, maintenance, reliability, safety, serviceability, ergonomics, environment etc.) | Make knowledge available to and directly usable for designers |
| Design Structure Matrix | Generate and process a matrix of precedence relationships (e.g., mathematical) among anticipated steps and variables in designing a particular system | Reduce the needed number of iterations<br>in a decision and optimisation sequence |
| Experimentation | By measuring and testing, obtain desired statistical values and trends | Determination of the properties of a realised TS, prototype, or test rig |
| Failure analysis | Observe and diagnose failures to establish causes and progresses | Obtain information toward "design for properties" |

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| Failure Mode, Effects, and Criticality Analysis (FMECA) | Analyse possible failure modes in a proposed system, establish possible consequences (“effects”) from each failure (as a network of interactions), estimate statistical probability of occurrence | Estimate reliability, durability, dependability of a proposed system, find ways of improving them |
| Fault Tree Analysis (FTA) | Analyse possible failure modes in a proposed system, establish possible consequences from each failure (as a hierarchical tree structure of interactions), estimate statistical probability of occurrence | Estimate reliability, durability, dependability of a proposed system, find ways of improving them |
| Fishbone diagram | Diagram main influences and causes on the behaviour of a system | Clarify sub-problems arising in solving a design problem |
| Focus Group Interview | Conduct interviews with potential customers as targets for a product | Establish customer requirements |
| Function costing | Perform regression analysis of the acquisition costs on a size range of a purchasable constructional parts | Obtain estimates of the costs of a proposed system |
| Function decomposition | Divide a more complex function into smaller and simpler functions | Redefine and concretise functions to allow easier solution |
| Fundamental Design Method | Use guidelines for goals to | Enhance creativity |

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| | start a design process | |
| Gantt chart | Show the time taken (planned or estimated) for a set of activities | Plan activities, with implied consideration of relationships among activities |
| Granta—Cambridge Engineering Selector (CES) | Select materials of construction and form (shape) from considerations of several material properties, and manufacturing processes | Optimise materials specification and usage |
| Ideals concept | Generate an ideal solution, degrade it to be able to realise it | Improve over existing systems by a leap |
| Incubation | After thorough preparation of the problem, take a break to allow the subconscious to work | Find solutions by intuition |
| Interaction net/matrix | Find interactions and relationships among features and variables for a system | Obtain an efficient sequence of establishing properties |
| Iteration | Starting from assumed values, obtain progressively closer approximation of values | Find solution for a system with complicated interactions |
| Life cycle Engineering | Take all phases of the life cycle into consideration, by formalized procedures | Minimise life cycle costs and influences on the environment |
| Market Research | Systematically collect and classify market information | Establishing marketing conditions |

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| Mind map | Map various concepts and their relationship to a central concept | Improve understanding of a related set of concepts |
| Morphological matrix/scheme | Enumerate possible organs (function carriers) to solve partial functions, in matrix form | Obtain many solutions by combinations of function carriers and variation in their arrangement |
| Objectives tree | Generate a list of objectives and sub-objectives (requirements and their priorities), diagrammed in the form of a hierarchical tree | Obtain a prioritised design specification, show relationships among requirements |
| Optimisation | Find an optimal solution to a problem, use mathematical techniques to find an optimal set of values according to a single criterion, or multiple criteria | Selection and improvement of solution proposals |
| Pareto distribution/diagram | Arrange observations according to magnitude from largest to smallest, give careful consideration to the largest | Focus on the most important issues |
| Pugh method | Concept selection method | Select an optimal solution among given proposals, and improve it |
| Quality function deployment (QFD) | Develop a set of charts according to recommendations to relate two viewpoints about a proposed product, a “house of quality” | Capturing the “voice of the customer” and making it heard throughout the product realisation process |

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| Rapid prototyping | Produce a tangible model of a constructional part or subassembly in a plastic (or metal) material under computer control, from a computer representation (solid modelling) | Obtain a solid model that can be handled, assess its suitability |
| Reverse engineering | Disassemble a realised TS (usually from a competitor) to generate a set of manufacturing documentation (detail and assembly drawings) | Copy a TS, or modify it in minor details |
| Strengths–Weaknesses–Opportunities–Threats (SWOT) Analysis | Analysis of a situation, by verbal analysis and quantitative evaluation | Formulate a vision and mission statement for an organisation |
| Structured Analysis and Design Technique (SADT) | Obtain flow chart of process to be investigated or to be designed, with chronological chart of alterations to keep track of developments, using interviews to gather information (facts, problem identification, opinions on solutions, etc.) | Define<br>transformation process, record progress of the design process |
| Taguchi Experimentation | By performing a set of controlled statistical experiments, find the main influences that can disturb the TS-operational process, or manufacture of the TS | Find robust solutions that withstand the disturbances |
| Taguchi philosophy | Reduce variation (variance, standard deviation) in | Make the product insensitive to variations in |

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| | properties, aim to achieve a consistent variation (statistical variance, standard deviation) of values around an optimal mean | external and manufacturing conditions |
| Tolerance analysis | Computer-aided analysis of tolerance accumulation and six-sigma limit determination | Find influences of tolerance contributions |
| Total Quality Management (TQM) | Continuous improvement of products' quality by applying techniques of quality control | Install and make permanent climate where employees continuously improve their ability |
| TRIZ | Computer-aided invention search method | Present<br><br>object information as analysed from numerous patents, to suggest a procedure<br><br>of invention that can be applied to design work |
| Weighted rating | Select criteria, assess weights for each criterion, evaluate<br><br>goodness of each solution proposal with respect to each criterion, multiply weight times goodness, add to obtain an overall rating or a percentage rating | Find relative goodness of each solution compared to a non-specified ideal |

As shown through the academic literature review, the use of prototypes is a valuable resource which should be used as much as possible to gain practical insights in how a concept idea will function in the real world. Also, being a way of helping to prevent design fixation from occurring.

Following on from this literature a technical literature review is to be conducted. This review will give an overview of different RP technologies, with the focus being on additive manufacturing. The reasoning behind this is that the majority of the front-end prototype is made up of components that have been made using additive manufacturing techniques.

## 2.2 Technical literature review of RP technologies

This section starts by first defining what RP is, it then goes on to investigate some different RP technologies, mainly focusing on the AM processes that are relatively accessible to both consumers and large companies. It breaks each down into what it is, pros and cons to using it and then gives a visual example of the produced product.

**Table 2.** *Literature review of various AM technologies*

| AM Process | Description | Pros/Benefits | Cons/Weaknesses | Output |
|---|---|---|---|---|
| FDM/FFF | Fused Deposition Modelling or Fused Filament Fabrication is a process of melting and selectively depositing a filament, made from a polymer such as ABS, PLA, etc. The filament is the polymer formed into a wire, in a diameter of either 1.75 or 2.85mm. | - No post printing curing<br>- Low price<br>- Wide variety of materials<br>- Easy material changeover<br>- Home/Office environment friendly<br>- Fast build times | - Small features, details and thin walls dictated by nozzle diameter<br>- Slow on large prints<br>- Requires support material on overhangs greater than $55^{o}$<br>- Supports can be difficult to remove |  |
| SLA | Stereolithography is the process of selective polymerisation of a photosensitive resin using an ultraviolet light source. The ultraviolet beam selectively cures areas on the top layer of the photosensitive resin contained in a vat. The bed lifts away from the vat allowing the resin to level itself, lowering the bed back down allowing the beam to cure the next layer. Repeating the process until the part is complete. | - Highly detailed<br>- Thin Walls<br>- Good surface finish<br>- Highly accurate<br>- Clear parts | - Requires post process curing<br>- Always requires support<br>-Limited materials (photopolymers)<br>- Warpage, shrinkage and curling<br>- Relatively expensive |  |

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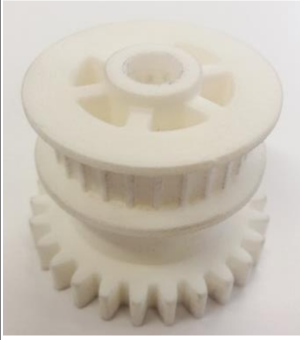
| SLS | Selective Laser Sintering uses a high-power laser to selectively melt and fuse a powdered material. The powder is spread using a roller to a precise layer thickness which is normally around 0.01mm. Due to the nature of the process the unsintered powder acts as a support material for the part. | - Variety of materials<br>- No post printing curing<br>- Limited use of support<br>- Relatively fast build times | - Rough surface finish<br>- Difficult material changeover<br>- Some post processing is required<br>- Mechanical properties are lower than the injection moulding process using the same material.<br>- Expensive |  |
| DLP | Digital Light Processing is similar to SLA in the fact that it uses photosensitive resin. However, instead of using a UV beam it uses a projector as a light source to cure the resin. This allows the whole layer to be exposed at the same time instead of being traced by a UV beam. | - Faster print times on large objects<br>- Can do very intricate parts<br>- Very accurate<br>- Clear parts | - Can only use small area of build area for detailed parts<br>- No batch production<br>- Layer formed using pixels<br>- Low detail on large parts |  |
| SLM | Selective Laser Melting is the process of using a laser to melt a metallic powder in selective areas. Similar to SLS a roller then covers the part with another layer of metal powder and the process repeats until the part is complete. Like SLS the metal powered not melted by the laser acts as a support material for the part/s | - Allows for part consolidation (reduce the number of components in an assembly)<br>- Limited use of supports<br>- Highly accurate<br>- Relatively fast build times | - Rough surface finish<br>- Requires post processing<br>- Difficult material changeover<br>- Expensive |  |

| | | | | |
|---|---|---|---|---|
| DMLS | Direct Metal Laser Sintering is very much the same as SLM using a laser to fuse a metallic powder together. The only difference is DMLS does not fully melt the particles of metal together whereas SLM fully melts them. | - Allows for part consolidation (reduce the number of components in an assembly)<br>- Limited use of supports<br>- Highly Accurate<br>- Relatively fast build times | - Rough surface finish<br>- Requires post processing<br>- Difficult material changeover<br>- Expensive |  |
| EBM | Electron Beam Melting is very similar to SLM producing very dense metal parts. The difference is instead of using a laser to melt the metal powder it uses an electron beam. It can currently only be used on a select amount of materials such as Titanium alloys and Cobalt chrome. | - Allows for part consolidation (reduce the number of components in an assembly)<br>- Limited use of supports<br>- Highly accurate<br>- Great power efficiency (80-90%) | - Limited materials<br>- Rough surface finish<br>- Requires post processing<br>- Expensive |  |
| 3DP | Three-Dimensional Printing uses ceramic powder which is layered onto a build plate. The print head which is made up of multiple ink jets then injects ink and binder into the ceramic material forming a layer of the part. More powder is spread onto and the process continues. This process allows for multi-colour parts to be created | - Allows for multi-colour parts<br>- Print heads are relatively cheap to replace<br>- Limited use of supports<br>- Reasonable build times | - Requires post processing<br>- Low Accuracy<br>- Damaged by water if not infiltrated with binder<br>- Brittle if not infiltrated with binder |  |

| | | | | |
|---|---|---|---|---|
| | using standard printing inks from a normal paper printer. | | | |
| DCJP | Direct Ceramic Jet Printing uses an ink that has ceramic powder contained within it. The main use is to create fine scale ceramic parts such as capacitors. The principles of DCJP have also been used with other materials such as carbon and zirconia. | - Allows for multi-colour, multi-material parts<br>- Limited use of supports<br>- Reasonable build times | - Expensive<br>- Still in development stages<br>- Requires the ink to be of a very specific type and formula |  |
| LOM | Laminated Object Manufacturing is a process that fuses layers of plastic or paper sheet using heat and/or pressure. This layer sheet is then cut using a blade or laser. Once the layer is cut a new sheet is place on top and the process starts again. | - No chemicals<br>- No enclosed chamber<br>- Large object easily created<br>- Models are relatively inexpensive to produce | - Low accuracy<br>- Doesn't produce functioning prototypes<br>- Machine is expensive |  |
| MJM/MJP | Multi-Jet Modelling or Multijet printing uses a piezo print head technology created by 3D systems to deposit a photo curable polymer resin or a wax support material, onto a print bed layer by layer. This allows parts with high resolution to be created, it also allows for the creation of parts with complex geometries that require support material. Due to the support material being a wax it means it can be melted out of the part after printing. | - Highly accurate<br>- High detail<br>- Limited user post processing required<br>- Good surface finish | - Expensive<br>- Limited materials (photopolymers)<br>- Always requires support<br>- Requires post processing |  |

Reviewing the main additive manufacturing technologies identified in the technical literature review. For the purpose of developing the front-end prototypes, namely the peristaltic version, a combination of a few processes should be adopted. The main process that would allow for fast production of components at low cost to be printed and tested, FDM should be used for most of the components. Where there is the need for more precision parts to be made either SLA or MJP should be used to produce the parts. If after some testing the components prove that they are fit for purpose, then it could be agreed that they be produced as SLS parts to fit in with the current front-end prototype.

With a clearer understand of prototyping and what signs to look out for to prevent a fixation from occurring. As well as the best additive manufacturing processes to use to develop the front-end prototype further. Now a project plan for the research going forward needs to be set out.

# 3 Project Plan:

## 3.1 Aim and Objectives

The following section is to define the overall aim of the research, along with the objectives that will be achieved.

**Aim**

To:

• Determine which of the competing technologies (screw or peristaltic) represents the optimum zero energy system for the Nano Membrane Toilet?

**Objectives**

To:

• Conduct a systematic literature review of the existing technologies for rapid prototyping and the theory behind prototyping and design thinking

• Identify the Research Question (RQ)

• Develop an Experimental Rig (ER) to compare the competing technologies

• Test the competing technologies using the Experimental Rig (ER)

• Analyse results and evaluate the competing technologies

• Disseminate findings through thesis and journal paper(s)

## 3.2 Research Question

Using the initial research topic given at the initial stages of the MSc by research, along with areas of interested created through past work using RP within the reinvent the toilet project. Has led to the following research question being defined:

Does RP provide an efficient route for the development and solution of critical competing technologies?

## 3.3 Methodology:

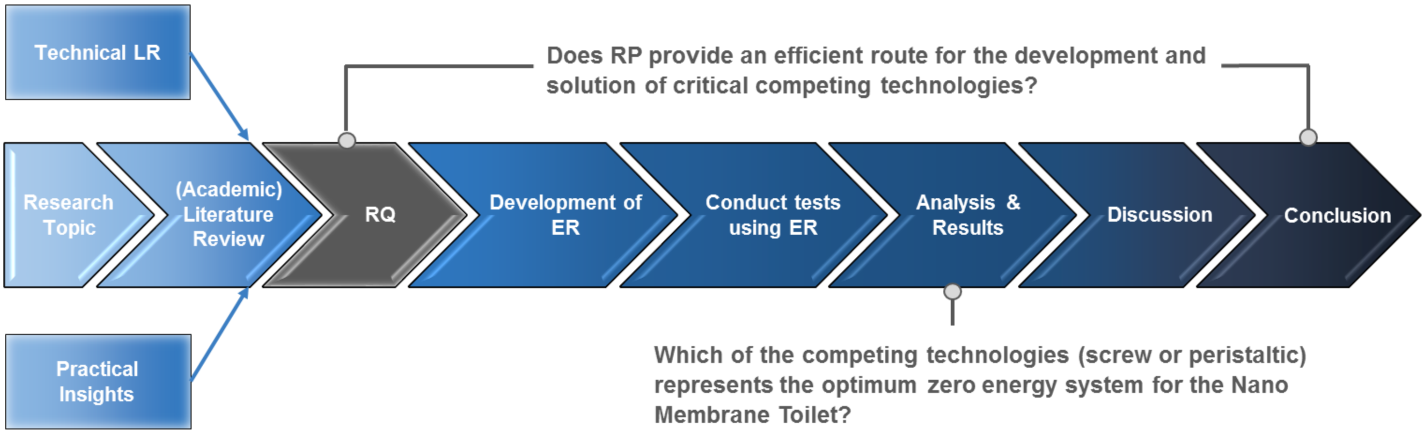



**Figure 6**. *Research Methodology*

## 3.4 Time Plan:

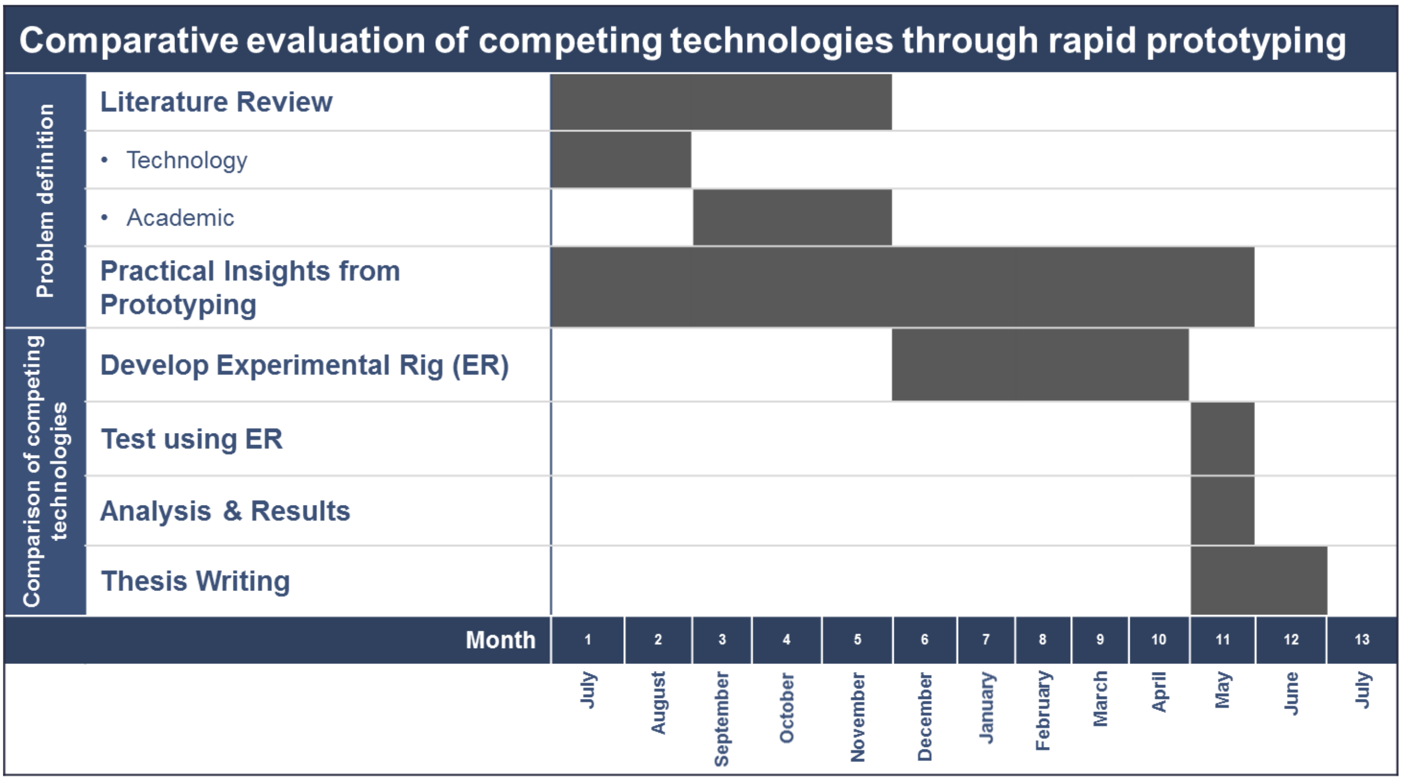



**Figure 7.** *Research Time plan*

# 4 Assessment of competing technologies:

## 4.1 Screw Background:

The Cranfield University Nano Membrane toilet in its current form, uses an Archimedes screw to lift sludge from the settling tank to the back-end. Created to capitalise on the settling phenomena or the natural separation of the urine and faeces, that is supposed to occur within the settling tank. The screw will only lift the solid material from the settling tank and any urine that is lifted with it will drain back down the screw as it turns. It has also been designed in a way that it dewaters the solid material as it lifts it up and out of the tank. In order to do this the screw sits within a cylindrical chamber that has an opening at the base, also referred to as the choke area, to allow the solids to enter at the bottom of the screw. This chamber and the screw are at 60º angle, this is due to the optimum angle for lift water is between 30º and 38º (Lakeside Screw Pumps, 2018), so it is steeper to allow for the separation of urine. To exit the screw chamber the sludge is forced through an aperture, which has also been tested to find the best bore size to induce a back pressure to aid in the dewatering.

Multiple versions of the screw unit where tested to find the best for the transportation of the faecal sludge. Each featured differing number of flights and pitch, as well as some which had starter flights, smaller or large overall diameter and tapering. From the testing it was determine that a screw with 15 flights, a tapering pitch from 4 to 0.5cm and a tapered diameter of 7 to 5cm, represents what is believed to be the best for this application. This screw was then integrated into the prototype prior to the next testing stage.

The prototype screw front end went through a stage of human user testing referred to as the HUT prototype. This prototype will form the basis for the Screw rig for the head to head test. It has been rebuilt and now includes the improvements that have been made to the current version of the toilet. As the screw version is still being developed any new modifications made to the current version can be fitted to the head to head rig. In order to make the testing as realistic as possible, making the end results relevant to the future work that is going to be conducted.

To make it easier to gain information for the rig such as the torque required to turn a fully loaded screw or the exact rpm that is required to lift the faecal sludge, whilst still dewatering, it is planned to motorise the screw. This will provide this feedback, information and allow for better control of the screw during working operation.

## 4.2 Peristaltic pump:

### 4.2.1 Background:

The lesser known peristaltic pump, represents the toilet from a design team lead approach. An initial version/ proof of concept pump was generated around the time of the screw testing. Being prototyped into a bolt on pump unit which could be fitted to the initial test toilet prototype. This proved to be successful in pumping the sludge from the settling tank to a holding tank. The idea that the secondary tank would be where the settling would occur, instead of settling before the transportation device. However, the pump was said to cause chemical changes to the urine and faeces due to it combine them into a slurry as it pumped, rather than just take out the solids from the mixture. So, it was side lined, and work progressed with the screw as the transportation mechanism.

Upon construction of the HUT 2 prototype of the screw, a new integrated pump and toilet prototype using many of the components from the screw version. Designed to be simple and robust system that had multiple subsystems driven from the lid. It had an integrated macerator, which was driven from the main pump rotor. It also had a feeder piston in the bottom of the settling tank which pumped out uniform shots of sludge every lift of the lid. The idea being that it would remove the need for another system to pelletize the sludge entering the dryer unit. This prototype known as PSPUv2 was only tested using water, which it was unable to pump. After this set back the PSPUv2 was left in storage, while work on further adaptations of the screw version took place.

Various changes and addition technologies to aid the screw in transporting the sludge have been suggested and tested, which has made the peristaltic a viable solution once again. This has created the need for a head to head test between the already optimised screw version, versus an optimised peristaltic pump version. This will, through a set of real world example tests, give a better idea as to which version is better at providing the desired output for the backend units.

To make it a fair test, the peristaltic pump version will need to be optimised to make it of an even standard to the screw. This will involve first testing the current and previous versions to get an idea of the issues with the new and any learnings from the original. Once this has been completed, the unit can then be redesigned, developed and then tested, with any issues been fixed before the head to head test.

### 4.2.2 Initial Testing

To compare the two current waterless toilet solution, namely the current Screw version and the lesser known Peristaltic pump. They both need to be to a similar standard and point in their development. The screw version has been developed across multiple teams and has been in development for multiple years. Meaning it is to a point in the current design where most of the issues have been addressed and no more changes can be made without the need for a total redesign. The other version the peristaltic pump was suggested as an alternative transport solution for the toilet. However, it was put to one side as it was feared the output of it would alter or interfere with the desirable inputs required by the technologies further along in the process. It was however developed into an initial integrated prototype using a few parts from the developed screw version, this took place during the construction of the original HUT (Human User Testing) prototype and display model. The aim of which was to have a plan B, if the screw version didn’t perform as required or expected. Although the peristaltic pump was integrated into a full front-end prototype it wasn’t anywhere near the development level of the screw version.

To fully assess the peristaltic unit and to identify areas in need of further development, tests were conducted using common loading that will be experienced by the toilet. These tests are simulated real world examples using miso paste as a simulant faeces. Miso has been used as simulant faeces by all of the teams working on the toilet project, since it began. It has been shown to be the closest thing to real faeces that is readily available, so to follow all the simulant testing that has been done before miso will be used for the tests.

As seen in figures 8 & 9 the areas of the peristaltic unit that will be tested and are of possible concern.

**Figure 8**. *PSPU v2 Rear*

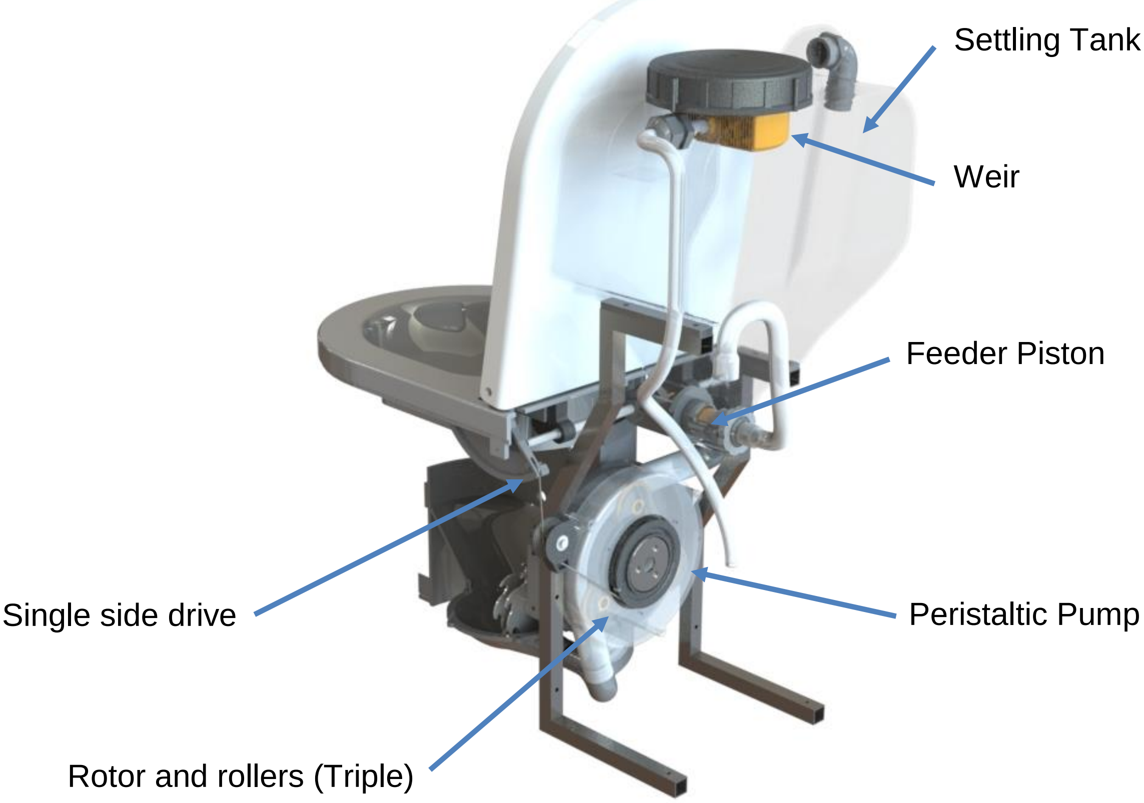


**Figure 9**. *PSPU v2 Front (section view)*


For the first tests the focus is on the macerator. The macerator is driven by gears from the main pump rotor on the rear of the unit. It is made up of two moving blades and two fixed blades moulded into the sump plate. The idea is the moving blades grab onto the material and pull it towards the fixed sharp blades attached to the bottom sump plate, shredding the material for the pump to then suck it through the sump exit port.

The first test conducted on the macerator was a simple water test (see table 3). This was purely to make sure the blades turn freely, as well as checking for any leaks from the macerator drive shaft (see figure 10).

**Table 3.** *Test table for the 1st Macerator*

| Macerator Test | | |
|---|---|---|
| | **Material/s Used** | **Results** |
| **1st Test** | • 1L of water | ✓ Success |
| | Observations:<br>The blades turn freely as they should | |

**Figure 10**. *Macerator 1st test only water*

The second test uses the same amount of water as the first but with the addition of some miso paste (see table 4). Will conducting each test observations are noted down so as to aid with possible redesign at a later stage. It is observed that the macerator in its current setup has a tendency to pull the material to either side of the blades. This maybe be an issue with the current setup as the pump pulls material from the rear of the macerator blades not the sides.

**Table 4.** *Test table for the 2nd Macerator*

| Macerator Test | | |
|---|---|---|
| 2nd Test | **Material/s Used** | **Results** |
| | • 1L of water<br>• 421g of Miso | ✓ Success |
| | Observations:<br>The blades turn freely as they should<br>The blades pull the material as the should<br>The material is pulled to either side of the macerator<br>All the material is broken up forming a slurry | |

As the macerator is showing no issues from the past two tests, it is now time to add toilet paper to the mix (see table 5). This test represents the first test either using simulant or real faeces to be conducted on either version of the front-end.

**Table 5.** *Test table for the 3rd Macerator*

| | Macerator Test | |
|---|---|---|
| **3rd Test** | **Material/s Used** | **Results** |
| | • 1L of water<br>• 421g of Miso<br>• 5 Sheets of single ply paper (400mm x 85mm) | ✓ Success |
| | Observations:<br>The blades turn freely as they should<br>The blades pull the material as the should<br>The material is pulled to either side of the macerator<br>The paper got caught on the exposed bolt and thread rod section<br>All the material is broken up forming a slurry | |
| | Redesign:<br>Enclosure or removal of the nuts and excess thread shaft | |

It was observed during the 3rd macerator test, that the paper had a tendency to wrap around the exposed section of the macerator shaft (see figure 11). It has been noted that this needs to be redesigned, either by enclosing the exposed end within the bottom section or removing the excess from the shaft.

**Figure 11**. *Macerator 3rd test paper caught on exposed shaft*

Even though a problem has been identified the macerator is still working as it is expected to. So for the next test more paper is added, but this time it is screwed up it to balls (see table 6). Once again the macerator is able to brake the material down into a slurry, with the screwed up paper posing no issue.

**Table 6.** *Test table for the $4^{th}$ Macerator*

| Macerator Test | | |
|---|---|---|
| | **Material/s Used** | **Results** |
| **$4^{th}$ Test** | • 1L of water<br>• 421g of Miso<br>• 5 Sheets of single ply paper (400mm x 85mm)<br>• 5 Sheets of the same paper screwed up | ✓ Success |
| | Observations:<br>The blades turn freely as they should<br>The blades pull the material as the should<br>The material is pulled to either side of the macerator<br>All the material is broken up forming a slurry<br>Screwed up paper posed no issue to the macerator | |

As the screwed up paper posed no issue to the macerator, more paper was added to the mixture (see table 7). This time some paper accumulation (see figure 12) was observed on the tips of the rotating blades, over time this may cause issues such as the macerator no longer functioning. It maybe that the blade profile needs to be altered or that the macerator needs to rotate at a fast RPM.

**Table 7.** *Test table for the 5th Macerator*

| Macerator Test | | |
|---|---|---|
| **5th Test** | **Material/s Used** | **Results** |
| | • 1L of water<br>• 421g of Miso<br>• 5 Sheets of single ply paper (400mm x 85mm)<br>• 10 Sheets of the same paper screwed up | ✓ Success |
| | Observations:<br>The blades turn freely as they should<br>The blades pull the material as the should<br>The material is pulled to either side of the macerator<br>All the material is broken up forming a slurry<br>Screwed up paper posed no issue to the macerator<br>Some paper accumulation on the hook of the moving blade | |

**Figure 12**. *Macerator 5th test paper accumulation*

On to the next test, which is the same as the last but with the addition of a plastic bag (see table 8). The reasoning behind this is currently there is no way of stopping large foreign bodies such as, toys, plastic bags, etc from entering the toilet. It is already expected that the plastic bag will cause the macerator to fail, what this test is to show is how it will fail and what if anything can be done about it.

**Table 8.** *Test table for the 6th Macerator*

<table>
<tr><th colspan="3">Macerator Test</th></tr>
<tr><td rowspan="4">6th Test</td><th>Material/s Used</th><th>Results</th></tr>
<tr><td>• 1L of water<br>• 421g of Miso<br>• 5 Sheets of single ply paper (400mm x 85mm)<br>• 10 Sheets of the same paper screwed up<br>• 1 piece of a Plastic bag</td><td>✗ Fail</td></tr>
<tr><td colspan="2">Observations:<br>The blades turn freely as they should<br>The blades pull the material as the should<br>The material is pulled to either side of the macerator<br>The plastic bag got caught on the exposed bolt and thread rod section<br>Blades bound up as the bag wrapped around both and became caught on the fixed blades</td></tr>
<tr><td colspan="2">Redesign:<br>Enclosure or removal of the nuts and excess thread shaft<br>Redesign the blade profiles or make the moving blades sharp</td></tr>
</table>

As expected the macerator failed when subjected to a tough material (see figure 13). This highlights the possible need for sharper blades or an alternative macerator design. It is unlikely that anything like a plastic bag or a large foreign object will be put into the toilet system. So similar to a conventional toilet in the home, if something too large to fit down the pipe is put in, it will block. The toilet will however have to potential process newspaper, which is a far tougher material than single ply toilet paper. This test also repeats the issue with the exposed retaining nuts and drive shaft being a cause for entanglement of material. This will need to be redesigned to remove this issue.

**Figure 13**. *Macerator 6$^{th}$ test plastic bag entanglement*

The final test in this series of macerator tests, removes the plastic bag and replaces it for a piece of nylon thread (see table 9). There is more potential for a piece of thread or hair to enter into the toilet system. As it has been previously observed the shaft, for the macerator blades, has a tendency to tangle. So it is expected that it will do the same here, but as the thread is a much thinner material will it tangle up easier in the blades.

**Table 9.** *Test table for the $7^{th}$ macerator test*

| Macerator Test | | |
|---|---|---|
| $7^{th}$ Test | **Material/s Used** | **Results** |
| | • 1L of water<br>• 421g of Miso<br>• 5 Sheets of single ply paper (400mm x 85mm)<br>• 10 Sheets of the same paper screwed up<br>• 1 piece of a Nylon thread (300mm length) | ✗ Fail |
| | Observations:<br>The blades initially turn freely as they should<br>The blades pull the material as the should<br>The material is pulled to either side of the macerator<br>The thread got caught on the exposed bolt and thread rod section<br>Nylon thread became entangled with the drive shaft and the front blade | |
| | Redesign:<br>Enclosure or removal of the nuts and excess thread shaft<br>Redesign the blade profiles or make the moving blades sharp | |

Once again, a failure caused by entanglement of the blades relating to both the blade profile and the excess drive shaft (see figure 14). These tests have given some great feedback in terms of design changes that need to be implement, in order for the macerator to have the best chance of breaking up the material for the pump.

**Figure 14**. *Macerator 7$^{th}$ test Nylon thread entanglement*

Proposed macerator next steps:

- Redesign the blade profile
- Reduction in the width of the blade
- Sharpening of blades
- Possible alternative solution

The next set of tests focusses on the original peristaltic pump which will be referred to as PSPU v1. This is the unintegrated pump, it is the proof of concept prototype. It is being tested to use as a comparison to determine if the changes made when integrating it into a full front-end system, have improved it or weakened its performance.

In order to conduct these tests the PSPU v1 has been piped into the PSPU v2 setup (see figure 15). This will allow the pump to pull material from the sump tank and pump it to the settling tank, in the same way the PSPU v2 should.

**Figure 15**. *PSPU v1 testing setup*

For the first test a simple water test is conducted (see table 10). This will see if the pump is firstly able to pump pure water, secondly what happens after it has stopped pumping and as an additional extra it will also show any leaks that may be in the system.

**Table 10.** *Results table for the peristaltic pump v1 1st test*

| Pump Test<br>PSPU v1 | | |
|---|---|---|
| 1st Test | **Material/s Used** | **Results** |
| | • 2L of water | ✓ Success |
| | Observations:<br>Water was successfully pumped from the sump tank to the settling tank<br>Leakage from the pellet piston at the bottom of the settling tank<br>Once pumping stopped water drained back into the sump tank | |
| | Solution:<br>Addition of some rubber seals to both sides of the piston<br>Possible addition of a 1-way valve | |

As the first test was a success and the pump is shown to be able to pump purely water. For the next test the addtion of Miso paste and toilet paper is made (see table 11). This will show how the pump hanldes the solids and also how it interacts with the macerator.

**Table 11.** *Results table for the peristaltic pump v1 2nd test*

| Pump Test<br>PSPU v1 | | |
|---|---|---|
| 2nd Test | **Material/s Used** | **Results** |
| | • 2L of water<br>• 500g of Miso<br>• 10 Sheets of single ply paper (400mm x 85mm) | ✓ Success |
| | Observations:<br>The mixture was successfully pumped to the settling tank<br>Rather than draining back down the tube to the tank, the falling solids blocked the pipe at the contact point between the roller and pipe<br>Settling of the pumped material occurred in the settling tank<br>If the material is not dropped onto or very close to the macerator it is not pulled into it and instead accumulates at the front of the sump | |
| | Solution:<br>Inclusion of slope to direct the falling material towards the macerator | |

Follow the 2nd test a plastic slope was added to the inside of the bottom section, the aim of which is to direct the waste material falling out of the bowl towards the macerator. The addition of the plastic slope should stop the material accumulating at the front of the sump, similar to what had been oberserved during the test.

Continuing the tests more toilet paper was added to the mixture (see table 12). This will show if adding the slope has had any effect on how the material enters into the sump.

**Table 12.** *Results table for the peristaltic pump v1 3rd test*

| Pump Test<br>PSPU v1 | | |
|---|---|---|
| 3rd Test | **Material/s Used** | **Results** |
| | • 2L of water<br>• 500g of Miso<br>• 20 Sheets of single ply paper (400mm x 85mm) | ✓ Success |
| | Observations:<br>The mixture was successfully pumped to the settling tank<br>Rather than draining back down the tube to the tank, the falling solids blocked the pipe at the contact point between the roller and pipe<br>Settling of the pumped material occurred in the settling tank<br>The slope meant all the material falling from the bowl was directed to the macerator this meant all the material was processed rather than sitting in a dead area<br>No simulant build up on the slope surface | |
| | Redesign:<br>Integration of the slope into the main tank body and sump section | |

After conducting the three tests with the PSPU v1 it has provided a baseline for the pumps capabilities. It has also highlighted some more improves that can be made to improve the input to the macerator giving it the best chance of effective material processing.

The next test is to check the performance of the PSPU v2, the front end integrated version of the pump. This pump has never been subjected to any proper or formal testing. To test how the PSPU v2 functions a simple test of water and miso to see if it is able to pump anything from the sump tank (see table 13).

**Table 13.** *Results table for the peristaltic pump test v2 1st test*

| Pump Test<br>PSPU v2 | | |
|---|---|---|
| 1st Test | **Material/s Used** | **Results** |
| | • 1L of water<br>• 250g of Miso | ✗ Fail |
| | Observations:<br>The main rotor assembly operated as it should.<br>Macerator worked as observed previously<br>No pumping of the mixture occurred<br>Any mixture that did get lift by the pump immediately drain back down the pipe once the rotor stopped | |
| | Redesign:<br>Total rethink on how the pump is mounted | |

Due to way in which the pump is mounted to the rear of the main tank, it requires the mixture to be pulled up before entering the main part of the pump. Observing how the PSPU v1 operates, the way in which it initial interacts with the material differs greatly from the PSPU v2. In the PSPU v1 prototype the input to the pump is level with the output of the sump, as soon as the mixture enters the main tank and sump it levels out. Meaning the pump always has material in the input, so always has some residual matter left to pump. It isn't trying to initially pull the air that's in the pipe and then the material before it has even begun pumping. Unlike the PSPU v2 which must pull the air through first then the material, by which point the lid is closed and all the material drops back into the sump. It is possible to get some material to be pulled into the pump if the lid is open and closed in very quick succession. However, this scenario will not be experienced by the front end, rather it will be infrequently used.

To get the pump working effectively it is proposed to move the pump down so that the input is at the same level as the output of the sump, similar to the PSPU v1. It is also proposed to increase the length of the pipe, so the rollers have more travel in contact with the pipe. Due mainly to the feedback from the pump experienced by the user through the lid. When the main rotor turns at some points during its travel, there are two rollers in contact with the pipe and only one at others. This makes the effort required on the lid more and less depending on whether one or two rollers are in contact. If the pipe entered the pump and exited it on the same side, it would mean that at any point in the rotors rotation the equivalent resistance of two rollers would be in contact with the pipe. This would mean the effort required by the user is the same through the full travel of the closing lid.

Considering all of the issues and problems that have been observed through the tests conducted. Below are the proposed next steps that need to be taken to develop the peristaltic pump further.

Proposed next steps:

- Redesign the main pump housing
- Adjust the mounting of the pump
- Increase the length of usable pipe within the pump

# 5 Redesign and development:

## 5.1 Motorisation of the Screw:

Currently the screw is powered by a constant torque spring, similar to the one used in the Freeplay wind up radio. This system is known as the accumulator as it stores the energy from the lifting of the lid until it is released after a certain number of lifts of the lid. This was to allow for the sludge to settle in the tank so that the screw can pump out the solids. It has been shown to work well, however some issues have been observed the main one being that the speed at which the screw turns is lower than that needed to lift the material from the tank. It is for this reason that the screw for the rig should be motorised, allowing for the screws speed to be at the correct level. It is also planned that the screw version will be able to be driven through the lifting of the lid, to allow for the comparison of the human effort required to lift the lid.

In order to make the motor quickly removable and also retaining the ability to replace the original gearbox at the top of the screw, a redesign version of the gearbox is proposed to be designed. This will be able to support both the motor and a torque sensor to give both control of and feedback from, the screw.

The design that was generated comprised of a redesigned gearbox, a spacer block and 4 sections of thread rod to compress the whole assembly to the v bowl assembly (see figures 16 & 17). It allows for all that was proposed, with the additional allowance for the removal of the torque sensor. Also integrated is a shaft seal at the top of the screw to prevent sludge entering the gearbox housing.

**Figure 16.** *Shaft seal mechanism*

Furthermore, to make allowance for the screw possibly not being perfectly cylindrical, a flexible coupling has been used. This should stop the screw binding against the side wall of the v bowl, requiring less effort on the motors part to turn the screw.

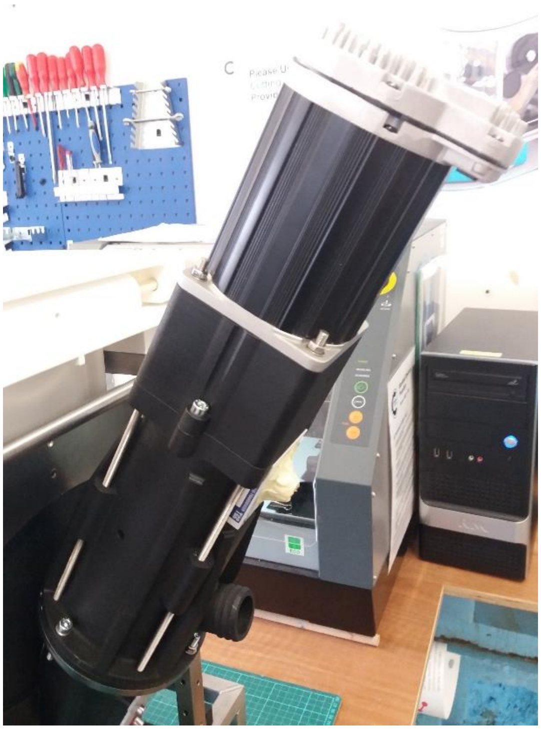


**Figure 17.** *The motorised version of the screw with a flexible coupling*

## 5.2 Peristaltic pump:

### 5.2.1 PSPUv3:

Due to the failures of PSPU v2 and the learnings gathered from the PSPU v1 the redesign of the pump and with it the creation of PSPU v3 took place. The main aim of this prototype is to prove firstly that having material initial drain into the pump as opposed to drawing it in. Secondly that having the input and output on the same side of the pump, not only slightly increase the through put of the pump but also the user experience through the lid.

The main thought is to make this version of the pump modular to make for easier component evolution, should any parts need further development. Also due to the limited time available to develop the pump before the head to head test, the components need to be as simple and robust to make manufacturing as fast as possible. To further reduce manufacturing time and cost, the redesign will reuse as many components as possible from the PSPU v2. This may be considered to lead to design fixation but, the fundamental way in which a peristaltic pump operates is already defined. The purpose of the redesign is to improve how the pump operates in the conditions and boundaries set by both the project brief and the current desired outcome as set out by the design team. Taking all of this in to account the following design was created, consisting of laser cut, FDM parts and existing components. It is designed to allow for easy alteration of the output pipe by simple removal or addition of a section of the external wall. It also allows the walls to be interchangeable adding the possibility of testing different contour wall sections with a corresponding roller profile. Furthermore, due to the PSPU v2 rotor design it allows for easy switch out of the rollers, allowing for testing of multiple diameters and roller profiles.

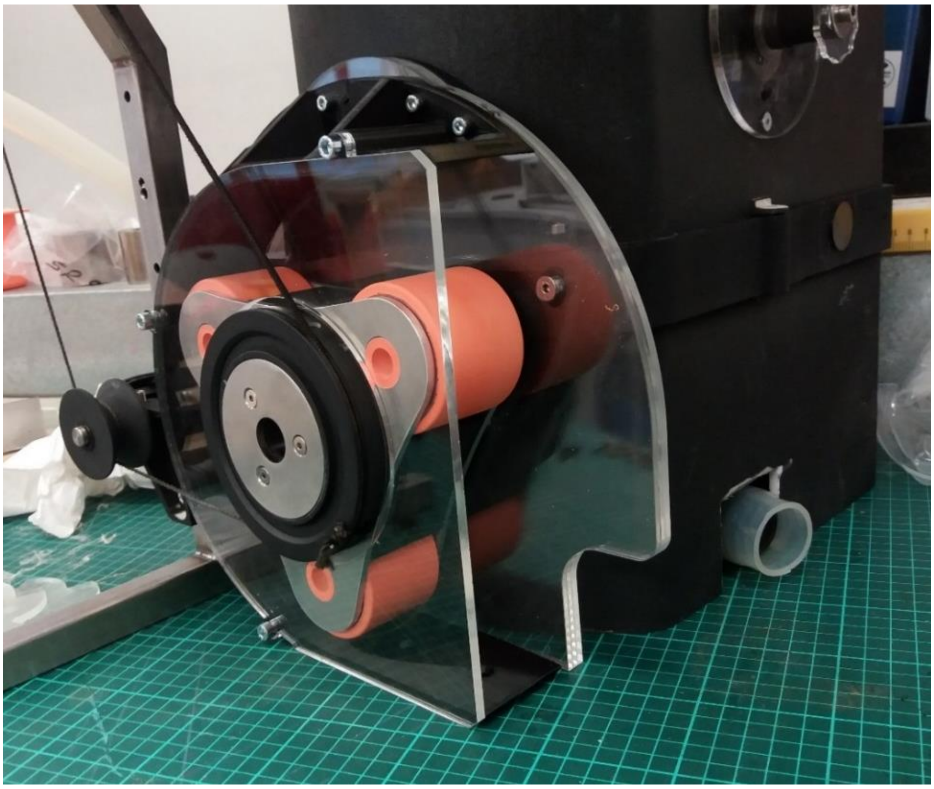


**Figure 18.** *PSPU v3 early stage*

As shown in the figure 18 the pump is now level with the base of main tank section. It can also be seen that the output from the sump is now located on the side as instead of the rear. Moving the sump output allows for less tight corners which have the potential of causing blockages, it also allows for possible integration of a one-way valve as proposed in the original testing.

To test whether the PSPU v3 a simple water tests the same as $1^{st}$ test conducted on the PSPU v1 was conducted. The results of the test are seen in table 14.

**Table 14.** *Results table for PSPU v3 $1^{st}$ test*

| Pump Test<br>PSPU v3 | | |
|---|---|---|
| $1^{st}$ Test | **Material/s Used** | **Results** |
| | 2L of water | ✓ Success |
| | Observations:<br>Water was successfully pumped from the sump tank to the settling tank<br>Once the pumping stopped water began to drain back into the sump however it was a slow drain rather than a fast release as seen before | |
| | Solution:<br>Addition of a 1-way valve | |

The first test of the PSPU v3 showed it performed well it was able to pump water much like the PSPU v1. However, unlike the PSPU v1 it was able to pump and hold the water in the pipe for a much longer period of time. This is one of the main issues with the PSPU it needs to be able to purge all the material from the sump tank including all the liquid. Unlike the screw version there is no weir for the water to over flow into, so all the liquid must be pumped to the settling tank. The idea to integrate a 1-way valve had been suggested before and was a recommendation after the initial tests.

### 5.2.1.1 Duckbill Valve:

Designed around and off the shelf duckbill valve, a three-part pipe fitting was made (see figure 19). Consisting of two plastic pipe barbs to connect from the sump output and to the input of the pump, and a rubber gasket to seal between both parts. The duckbill valve can be seen through a clear piece of connecting pipe allowing for visual assessment of the valve in operation. Installation is a simple task due to the modularity of PSPU v3, as well as the allowance for the valve already being made.

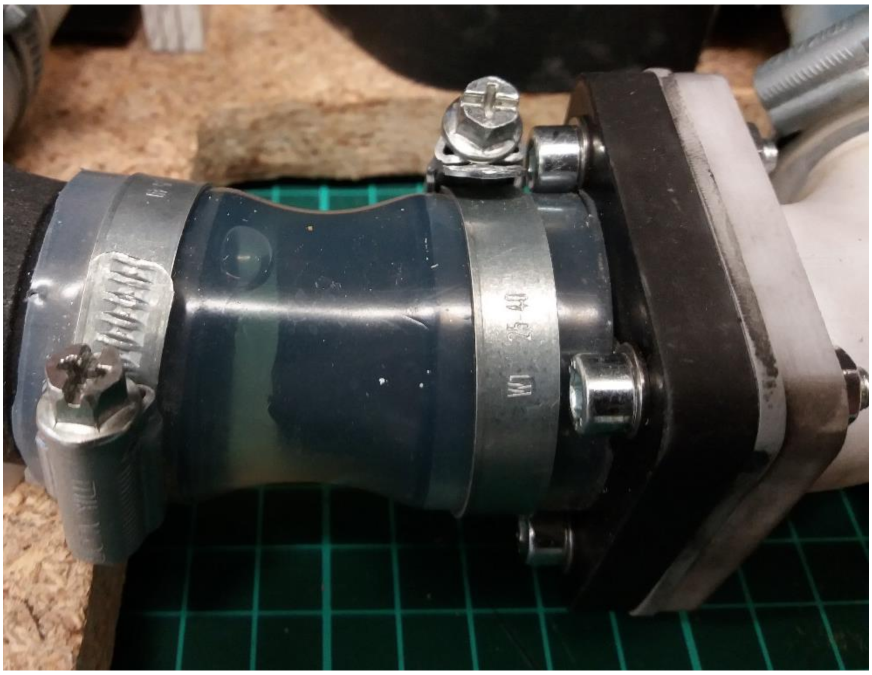


**Figure 19.** *Duckbill valve view port*

Following the installation of the duckbill valve the same test as before was conducted with the following results (see table 15).

**Table 15.** *Results table for PSPU v3 2nd test*

| Pump Test<br>PSPU v3 | | |
|---|---|---|
| 2nd Test | **Material/s Used** | **Results** |
| | 2L of water | ✓ Success |
| | Observations:<br>Water was successfully pumped from the sump tank to the settling tank<br>The duckbill works as expected hold most of the water within the tube after the pump<br>Some liquid still returning through the valve, but with some solids in the mixture this will almost certainly stop. It is also due to an air bubble forming on one section of the duckbill<br>Some leakage from the pipe barbs, due to the extra pressure on the connections | |
| | Solution:<br>Lowering of the duckbill in relation to the pump and sump, to remove the air bubble<br>Pipe clips on all connectors to stop leakage | |

After this test was conducted, clips where added to all pipe connections to ensure no leakage and the valve was also lowered removing the air bubble allowing it to function correctly.

#### 5.2.1.2 Feeder Piston:

The next part to address is the feeder piston located at the bottom of the settling tank. This device is driven off by a cam attached to the odour mechanism shaft. The idea is that cam pushes a plunger in and out within the settling tank. By doing this it causes pellets of sludge to be pushed out of the settling tank into the top of the dryer unit. The current version has issues with leakage both from the front section where the plunger doesn’t seal in the extended position and in the rear where the plunger sits in the main body of the feeder unit.

The initial idea was to make a new plunger with grooves in which O-rings would be seated, however on investigation it was shown that O-rings would not perform very well in a sliding motion device usual resulting in the O-rings failing. So instead a two-part feeder body was designed (see figure 20). It has a hydraulic seal on the entry of the piston shaft to seal when in motion and at rest. The slot in which the sludge feeds into the piston, was also enlarged to allow for nuts or other hard objects to pass through.

**Figure 20.** *Original Plunger/ Feeder vs V2 Feeder*

Some initial testing was conducted on the feeder piston to check for leakage as this part has been the main source of leakage that has been experienced throughout the testing. The results are as follows (see table 16).

**Table 16.** *Results table for Feeder Piston v2 1st test*

| | Feeder Piston V2<br>PSPU v3 | |
|---|---|---|
| 1st Test | **Material/s Used** | **Results** |
| | 2L of water | ✓ Success |
| | Observations:<br>Water was successfully held in the settling tank<br>Some leakage from the gasket seals | |
| | Solution:<br>Use some sealant between the gaskets and the settling tank | |

The redesigned feeder piston showed a vast improvement on the original with no leakage occurring from the actual piston itself. As stated in the solution the leaks are occurring on the contact faces between the gasket and the settling tank itself. This is due to the faces not being parallel to each other. This is a minor fix and now means all the leaks have been sealed.

#### 5.2.1.3 Drive mechanism:

The final part that needs addressing is how the pump is driven on PSPUv2 and on the tests conducted on PSPUv3 it has used a length of bicycle brake cable pulled by the lid and a piece of elastic to retract the ratchet centre part back after the lid is opened. This system works however it has a few problem areas.

#### 5.2.1.4 Problem Areas:

##### *5.2.1.4.1 Single sided drive:*

Due to the pump only be driven on one side (see figure 21), it causes the lid to twist.

**Figure 21.** *Single side drive*

***5.2.1.4.2 Jockey wheel:***

As the lid is shut it pulls the cable upwards this causes the pump to rotate. However, the pump is perpendicular to the lid so the cable has to be guided. This has been done with a small jockey wheel on a bracket (see figure 22). This bracket has a tendency to bend when under loading from the closing of the lid, making the effort required by the user to be high.

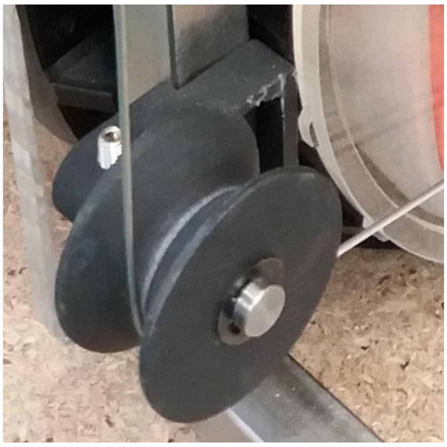


**Figure 22.** *Jockey Wheel*

***5.2.1.4.3 Ratchet:***

Does work, however when the springs are removed to reduce the noise level, there is a dead spot where all the teeth will be out of engagement. This causes the pump to stop turning, which will then require it to be turned manually to get the teeth to reengage.

In order to eliminate the issues listed above a redesign of the pump drive system is required, this will be known as PSPUv4.

### 5.2.2 PSPUv4:

This new version of the peristaltic pump will take all the learnings from the previous version and combine them with new solutions to the identified problem areas from PSPUv3. Leading to a more refined overall system design which will represent the developed version of the peristaltic pump toilet. This can then be tested against the screw version of the toilet.

#### 5.2.2.1 Drive:

The majority of the identified problems are related to how the pump is driven. The ideal solutions would mean the lid drives the pump on the opening and closing movements. This will roughly double the throughput of material, getting closer to meeting the required volume per day. It could also reduce the effort required by the user, as well as stopping the lid twisting.

The idea that was settled on was to create a gearbox (figure 23), made up of three bevel gears. Two 15 tooth bevel gears would be the drivers, a 30 tooth gear would be the driven gear. Each of the 15 tooth gears is integrated into a ratchet mechanism. This means they will only be driven in one direction, the other direction they will freewheel. These combined with the large 30 tooth gear form the gearbox.

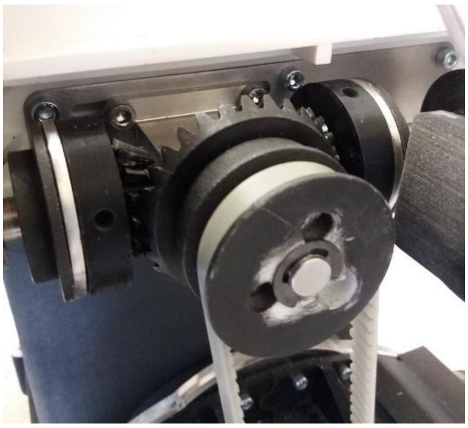


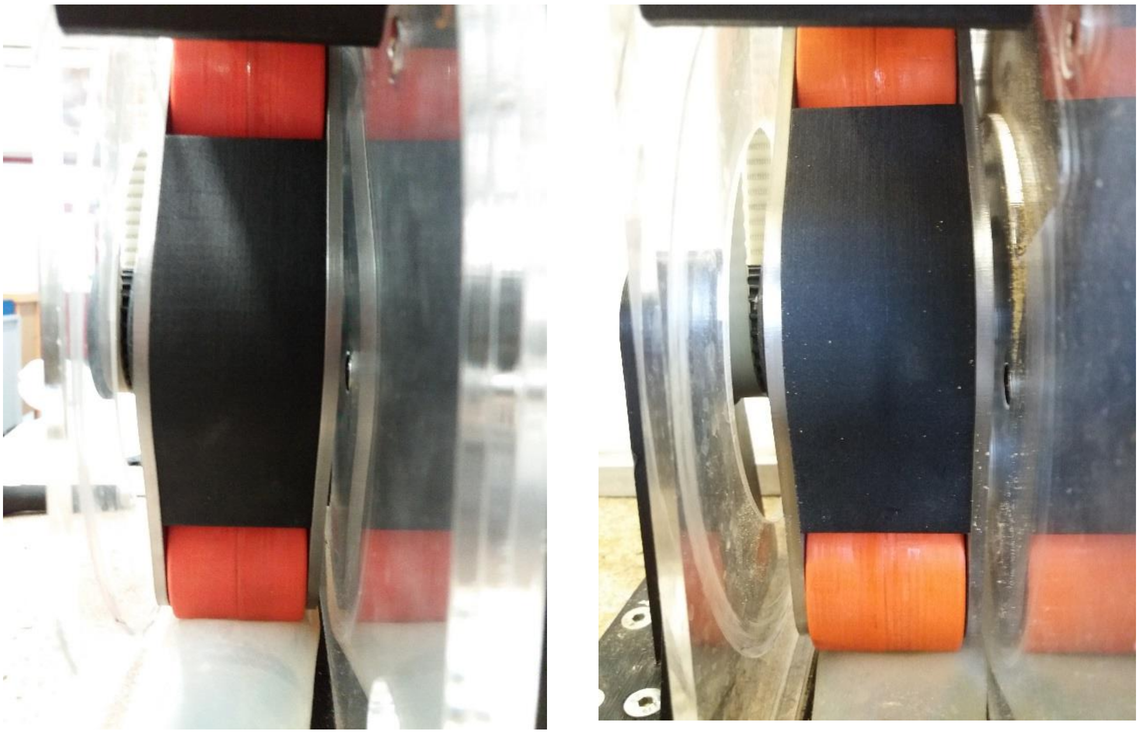
**Figure 23.** *Gearbox*

Due to the gearbox being relatively compact, as well as requiring the smaller gears be driven in both directions, it's able to be integrated with the already existing odour mechanism shaft. This integration of the gearbox and the odour mechanism shaft eliminates the problem of a single drive as both sides of the lid already drive the odour mechanism. Meaning the shaft rotates on the open and the closing of the lid, rotating the ratchet/gear assemblies.

The next point to address is how the gearbox transfers drive to the main rotor. On PSPUv2 and v3 this was done through a piece of paracord on the early tests, which was later swapped for a length of bicycle brake cable. This drive system worked however, due to the difference in the angles between the lid arms and the main pump. It meant the need for an idle wheel/ jockey wheel, the job of which is to guide the cable. This jockey wheel and bracket are subjected to high loading forces, as the cable is always under tension. In the tests that where conducted this bracket acted as a cantilever beam, meaning it bent towards the pump when a pulling force acted upon the cable. This bending lead to excess tension on the cable which meant the user was required to apply more force when lifting the lid.

After considering a possible redesign of the bracket and using a similar method, it was decided to change to a belt and pulley system. This would remove the need for the jockey wheel, at the same time removing the need for two cables to drive the pump rotor. Using a belt and pulley also reduces the number of components require on the rotor of the pump. Due to the gearbox driving the pulley belt in one direction, there is no longer a need for the integrated ratchet on the rotor. This removal of the ratchet addresses the problem of disengagement of the rotor, stopping the need for manual assistance.

One problem that was observed when the pulley belt was added to the assembly was main rotor of the pump being bent upwards (see figure 24). Due to the way in which the pump was originally designed it meant that the main shaft that the rotor rotates around is only fixed at the back of the pump. Due to the tension put on the pulley belt it means the shaft bends up. This has the knock-on effect of the rotor hitting the back wall of the pump on the top edge, creating excess friction between the two surfaces. Leading to an increase in effort required from the user as well as the belt jumping teeth.



Before After

**Figure 24.** *Before and after rotor* alignment

To stop the main shaft bending it needs to be constrained at both ends. Adding a 3DP bracket at the front of the pump, along with a longer main shaft, negates this problem. As can be seen in the images above, before the bracket was added the rotor contacts at the top of the back plate. After the addition of the bracket the rotor now sits central within the pump housing.

Solving that problem means that the pump now runs freely, with a reduction in the effort required by the user when opening and closing the lid. It also means the peristaltic pump version (see figure 25) of the toilet is now optimised enough to be fairly compared with the screw version. The results of which will be inputted into a matrix system to allow for ease of comparison between the two.

**Figure 25.** *PSPU v4 complete system*

# 6 Head to Head test:

As both prototypes have been developed to a point where they represent the most optimised and best operating versions that have currently been produced. It is now time to test them against each other, measuring a number of different aspects of the overall workings for each. These values or results will then be implemented into a matrix, which can then be used as a way of comparing them to determine which system represents the better transportation method.

Due to expansion of the department, a specialised testing lab has become available and has been modified to accommodate the conduction of the head to heads testing.

## 6.1 Overview (Work area):

To conduct the head to head test in the most scientific way possible a specialised work area has been setup in a new lab. It has been layout and designed specifically with this test in mind. It consists of a raised work area that is around 500mm in height. This raised bench allows for ease of used to operate the prototypes, also allowing for any work to be carried on them without the need to bend down for extended periods. Contained within the bench is an open drain with two entry ports to allow pipes from the exits of the toilets to be feed into. This drain can then be flushed using a standard flush system from a toilet. The ability to drain away any waste, allows for the possibility to use real faeces in future tests (if needed). On the opposite side of the room there is a sink with both hot and cold running water to allow for easy cleaning and filling of the prototypes. All of this allows the test to be conducted and contained to one room with no need for any equipment to be brought into or removed from it. The bench is also large enough to accommodate additional prototypes tested on it, either adding to the test in future or purely solo testing purposes.

## 6.2 Test Rig:

### 6.2.1 Setup:

#### 6.2.1.1 Screw:

It was previously discussed that the screw version of the toilet would be motorised for the head to head test. However, due to the same motor setup being used on a test rig in South Africa, the results of which have provided some valuable insights into how the settling tank works and the RPM required for the screw to pump. It has been agreed that the screw version should be converted back to the fully mechanical version. This will allow for two fully mechanical front end systems to be tested against each other. Furthermore, the test rigs both are within the initial brief, as set out at the start of the project. Which was to design a system which requires no external power sources, such as electricity. Also having the mechanical version of the screw allows us to test a new spring release mechanism in a few simulated real-world scenarios.

After converting the screw version from the motorised version to the mechanical system, as seen in figure 15, it was then a case of fixing it to the work bench. This was due to the force require by the user to lift lid, coupled with the fact that the frame the toilet sits within is not level. Meaning the whole prototype tipped backwards when the user opens the lid. After securing the prototype to the bench, using some right-angled brackets, the screw version was setup for the tests to be conducted upon it.

#### 6.2.1.2 Peristaltic:

The newly developed version of the peristaltic pump PSPU v4 will be the used in the Head to head testing. As this now represents the most developed and optimised version of the peristaltic at this current stage in the project. To setup the PSPU v4 for the testing it is a case of connecting the waste pipe to the waste drain.

### 6.2.2 Overview (Final setup):

With both prototypes in place and plumbed into the waste drains the test setup is complete, as seen in figure 26.

**Figure 26.** *Test rig setup*

As the setup for test is complete the next step is to set out the test plan for the experiment/s this is to ensure all areas that need values to be given for both the screw and peristaltic will be investigated.

## 6.3 Research Question (Experiment)

The following research question is to be answered through the conduction of the head to head test.

Which of the competing technologies (screw or peristaltic) represents the optimum zero energy system for the Nano Membrane Toilet? The answer to the question will add additional information to the knowledge base of the wider team, with the hopefully continued development of which every system proves itself to be the best.

## 6.4 Testing Plan:

The main focus of the test is to determine which transportation system is better. This will be done by conducting a range of tests, each be conducted on each prototype. The main test involves the loading of a simulant faecal sludge mixture into both prototypes and recording the outputted material. During the conduction of these tests observations as to how the systems operate will be made, with the results being used in the matrix system that will be created upon completion of the test.

## 6.5 Results Analysis:

### 6.5.1 Results:

#### 6.5.1.1 Force required to lift the lid:

**Table 17.** *Force test result table*

| | Force (N) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Test** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **Mean** |
| **Screw** | 71.9 | 81.9 | 69.9 | 51.1 | 56.8 | 59.2 | 72 | 65.6 | 68.8 | 74 | 67.1 |
| **PSPU** | 13.6 | 11.9 | 12.9 | 8.6 | 10.9 | 10.9 | 10.3 | 9.7 | 8.8 | 11.2 | 10.9 |

**Table 18.** *Force required converted to Mass result table*

| | Mass (kg) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Test** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **Mean** |
| **Screw** | 7.3 | 8.4 | 7.1 | 5.2 | 5.8 | 6 | 7.3 | 6.7 | 7 | 7.5 | 6.8 |
| **PSPU** | 1.4 | 1.2 | 1.3 | 0.9 | 1.1 | 1.1 | 1.1 | 1 | 0.9 | 1.1 | 1.1 |

### 6.5.1.2 Noise Level:

**Table 19.** *Noise level result table*

| | Noise Level (MAX dB) | |
|---|---|---|
| **Screw** | 82 | Windup |
| | 83 | Release |
| **PSPU** | 71 | |

### 6.5.1.3 Transportation Tests:

**Table 20.** *Transportation tests results*

| | | | Screw | | | PSPU v4 | | |
|---|---|---|---|---|---|---|---|---|
| **Water (L)** | **Solids (g)** | **Toilet Paper (sheets)** | **# of Lifts** | **# of Lifts needed** | **Amount of sludge pumped out** | **# of Lifts** | **# of Lifts needed** | **Amount of sludge pumped out** |
| 2.5 | 0 | 0 | 70 | 70 | ALL | 70 | 60 | ALL |
| 2.4 | 100 | 16 | 70 | 70 | 2.06kg | 70 | 60 | 2.28kg |
| 2.2 | 300 | 40 | 70 | 70 | 1.29kg | 50 | 50 | 2.22kg |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1.875 | 625 | 80 | 40 | - | 1.2kg CLOG | 70 | 55 | 2.24kg |
| 1.5 | 800 | 80 | 70 | 70 | 2.07kg | 70 | 55 | 1.92kg |
| 1 | 800 | 80 | 30 | - | 51g CLOG | 70 | 60 | 575g |
| 0.5 | 800 | 80 | 70 | 70 | - | 70 | 70 | - |
| 0.25 | 800 | 80 | 70 | 70 | 30g | 70 | 70 | - |
| 0.05 | 800 | 80 | 70 | 70 | - | 70 | 70 | - |
| 0 | 800 | 80 | 70 | 70 | - | 70 | 70 | - |

| Colour Code: | |
|---|---|
| | Success |
| | Failure |

## 6.6 Results discussion:

The results of the set of tests along with the observations made whilst conducting the tests have provided some very valuable insights in to both versions of the toilet. This section will discuss some key findings that were made during and through conducting the head to head test.

### 6.6.1 Force required:

One of the main values that was required to be measured, was the force required to lift the lid. This is important from a user perspective as too high of a force and a child won't be able to use the toilet without adult help. Also, the idea that the toilet is supposed to require as little effort from the user as possible, so if the lid is hard to open due to the need for excess force there is the potential they will use the easier option of the current pit latrines.

As can be observed from the recorded results, the force required to lift the screw versions lid varied from 51N to just under 82N. The average force required to lift the lid was 67.12N which is the equivalent of lifting 6.85kg of weight, calculated by dividing the average force by 9.8 which is the equivalent of 1kg of weight at sea level on earth. Following the same test procedure, the forced recorded for the PSPU varied from 8.6N to 13.6N averaging out at 10.88N. Which following the same calculation as the screw works at a weight of 1.11kg. This means the PSPU requires just over 6 times more force to open the lid, the equivalent of an extra 5.74kg of weight to be lifted by the user to be lift when opening the lid.

### 6.6.2 Noise Level:

The amount of noise the toilet makes although not critical to the way in which it functions it is a big issue from the user’s perspective and how they perceive how the toilet is functioning. For the screw version two tests were conducted on measuring the sound level when opening the lid winding up the spring, and the other release all the stored energy and turning the screw. The results of these two tests only had 1dB difference between them giving a reading of 82dB on the winding phase and 83dB on the release stage. It must be mentioned that these values represent the maximum sound level recorded during both phases of the screws operation. One of the observations made when lift the lid and winding up the spring was that the noise was almost disconcerting, sound as if parts where straining and about to break. These kinds of sounds would lower the user’s perception of how well the toilet is operating, making the assumption that this noise could mean the toilet is about to fail. Although this is not quantifiable is a valuable piece of qualitative data, because even the quietest noise if perceived as a bad sound will lower the user’s faith in the product. With this project being about providing a product which is almost alien to a lot of the aimed at users, that faith is something that needs to be kept if it is to be adopted as the new normality.

Looking at the sound level recorded from the PSPU it maxed at 71dB, 11dB lower than the windup of the screw. As with the screw observations where made as to how the sound made the user feel about the toilets operation. However, unlike the screw version the peristaltic sound is constant on both the lift and closing of the lid. It doesn't vary in tone, it is a continuous, consistent level through the whole travel of the lid. This gives the user some peace of mind that the toilet is operating well as the sound is always the same.

### 6.6.3 Transportation capability:

This is the most critical test conducted during head to head, the results of this paint a very vivid picture as to the benefits and weakness of each of the transportation system.

#### 6.6.3.1 Screw:

Looking at the results, it can be seen that the screw version of the toilet was able to purge all 2.5 litres of water, with no solid content put into the settling tank. Although this shows the screw is able to pump from the settling tank, this shows the screw doesn't do as it is design to. The purpose of the screw is to dewater the sludge from the settling tank. If it was working as it should only a small amount of the water should have been evacuated from the settling tank, this is due to the screw not being able to 100% dewater. The next couple of test show similar results and although the full volume that enters the system is not being purged out, looking at the material that is pumped out (see figure 27) it is mostly water that is pumped. Highlighted in blue on the results table, this test represents the expected liquids and solids from a household of 10 people. This is the guidelines that have been used when design and testing all components of the overall toilet design. As can be seen in the results table the screw failed after only 40 lifts due to the screw clogging.

**Figure 27.** *Screw blockage*

In figure 28 it can be observed that the screw blocked with toilet paper. Previous tests conducted on the screw did not make allowance, nor did they test using any toilet paper. Stated earlier the head to head test is a simulated real-world test so toilet paper, as would be used in normal toilet use, has been added. This blocking caused by toilet paper demonstrates the need for either a redesign of the screw, or the housing in which it sits. Either way it shows a major issue with the screw not being able to transport material from the settling tank if, the material happens to be fibrous such is the case with the toilet paper.

After completion of the critical test, more solids where added and the liquid reduced. In theory the screw should perform better in these tests as it is designed to handle solids. As shown in the table of results the screw was able to pump out the majority of the material from the settling tank, leaving some brown liquid at the bottom of the screw see figure 28. Moving on to the next test once again the screw clogged due to the toilet paper requiring manual assistance to unclog the system.

**Figure 28.** *Screw liquid separation*

By conducting the simulated tests, it has shown that although the screw is able to pump material from the settling tank and also that the spring has enough power to work in most situations. It highlights that the screw doesn't dewater as it should, instead pumping pure liquid better than pumping mostly solids. But more of an issue is the fact that the screw blocks when fibrous material, such as toilet paper, enters the system. To overcome this problem a major redesign needs to be consider if, the screw transportation method is continued to be used within the toilet design.

**6.6.3.2 Peristaltic:**

Following the same tests as the screw, the peristaltic showed that it is able to pump pure water by purging the whole tank. It also did this in under 70 lifts doing it in 60 so it has an allowance for any material draining back through the system. As it can be seen in the results table the PSPU manages to pump consistent with ever increasing solid contents. It should be noted that it has been observed that the pump self-primes and once primed it stays primed, due to some of the material remaining in the output tube of the pump. This means the pump always has material being pushed through it, as seen in figure 29.

**Figure 29.** *PSPU output tube holding* liquid

Conducting the critical test showed that the peristaltic is more than capable of pumping the expected daily material intake. It also managed to empty the sump tank in only 55 lifts, which shows that its efficiency has been vastly improved on this current version when compared to its predecessors. Furthermore, the amount pumped out of the system is still consistent with the earlier tests. Another point that should be raised is the peristaltic has no issues with the toilet paper. On this test when conducted with the screw it blocked due to the toilet paper, meaning it had to be manually driven to remove the toilet paper. The lack of issue with the toilet paper can be accredited to the fact the peristaltic has a macerator driven by the rotation of the pump rotor. Adding little to no loading on the lid opening and closing this macerator seems to be a wisely implemented system which is more added value to the overall system. Following on the next test which sees a further reduction in the liquids, shows the pump is still able to pump out the sump tank, although it should be noted there is a small reduction in the outputted material. Continuing with the reduction in liquid this test with only 1 litre of water and 800g of solid combine with the 80 sheets of toilet paper would prove a challenge to the peristaltic resulting in only 575g of material being removed from the sump tank. Testing with a further reduction in liquid the pump seemed to be able to pull some of the sludge out of the sump but due to the lack of liquid was unable to pump it in to the settling tank (see figure 30).

**Figure 30.** *PSPU output tube sludge*

It was to be expected that the peristaltic pump would struggle with the lack of liquid being present within the sump tank, as it is needed to make the peristaltic pump operate. What was surprising was that it was able to pump a higher percentage of solid to liquids than was expected, so it does have a factor of safety in the event of reduced liquids within the sump tank.

Through conducting the tests, it shows that the pump, in the simulated real-world tests, is more than capable of pumping the required material from the sump tank. It is able to do this within the maximum amount of lifts, doing so with 10 – 15 lifts to spare. Furthermore, it has shown that the peristaltic also has a factor of safety when it comes to both he more liquids and the more solid scenarios should these ever occur. In addition, it has shown that it is able to handle the addition of toilet paper to the sludge, with it pose little issue to the over working and user experience of the transportation system.

## 6.7 Next steps:

As the head to head test has been conducted and the results analysed the data is now to be implemented into a matrix system. The matrix will allow other members of the wider team to be able to see both the quantitative measurements, as calculated and proven through the conduction of the test. But also, the qualitative measurements as collected through observations made during the experimental testing of the prototypes. The aim of the matrix is to give each of the systems a score so that the one with the better score should represent the better of the competing systems and should be the one to have continued development done to it.

## 6.8 Matrix System:

The matrix system as mentioned previously is a system which uses both quantitative and qualitative values to give an overall score to each of the transportation systems. These measures of merit are then added together for each section, with the qualitative section being subtracted from the quantitative section. The output value is then used as the score for the overall system, this score can then be easily compared, in this case it is between the screw and the peristaltic but further systems could be tested and the results placed in to their own matrix giving a score that can also be compared.

### 6.8.1 Screw:

Applying the results of the screw into the matrix in the quantitative section and the observations made during the testing being inputted into the qualitative section. The overall score for the screw version is -8.

### 6.8.2 Peristaltic:

Doing the same as with the score inputting both the measured values from the head to head test, along with the observed values. The peristaltic ends up with an overall score of 1.

## 6.9 Score comparison:

Now that both systems have a score it is quite clear which is the more stand out transportation system. Which with an overall score of 1, is the peristaltic pump system. This system showed better results in the quantitative section due to its lower force requirement from the user when lifting the lid, coupled with a great pumping volume per lift. Also faring better in the qualitative areas, with better serviceability and general robustness. To anyone who looks at these two matrix scorecards it is clear which of the systems is the better transportation system. However, it must be mentioned that the qualitative measurements although they were measure from a non-biased viewpoint, they are still subjective and therefore could be consider bias by other members of the wider team. Regardless of this the matrix system developed to display the results of the head to head test ad possible further tests, gives a more visual way to convey which design is better and in which areas it is lacking. In addition, it also allows systems that may work in different ways and are therefore non-comparable as straight like for like systems, the ability to be compared trough a simple score.

# Screw Transportation System

TRL: **4/5**

Description:

**Archimedes screw version of the transportation system**

Render:

Value:

- Science lead design
- Potential for dewatering

**System Evaluation**

| | | | | | | |
|---|---|---|---|---|---|---|
| Effort to lift the Lid | >40N | 30N | 20N | <10N | 1 | Quantitative |
| Pumping Volume (per lift) | <0.05l | 0.05 – 0.15l | 0.15 – 0.25l | >0.25l | 1 | Quantitative |
| Blockage Size | <1cm³ | 2cm³ | 3cm³ | >4cm³ | 1 | Quantitative |
| Complexity (parts) | >100 | 90 | 80 | <70 | 4 | Quantitative |
| Noise Level | >85dB | 75dB | 65dB | <55dB | 3 | Quantitative |
| System Integration | No Issues | Minor Issues | Issues | Major Issues | 4 | Qualitative |
| Serviceability | Simple | Relatively Simple | Average | Poor | 3 | Qualitative |
| Robustness | High | Medium | Average | Low | 3 | Qualitative |
| Efficiency | High | Medium | Average | Low | 3 | Qualitative |
| Dewatering | Fully | Partial | Minimal | No Effect | 4 | Qualitative |

Overall Score **-8**

**Figure 31.** *The score matrix for the Screw*

# Peristaltic Transportation System

TRL: **4**

Description:

**Peristaltic pump version of the transportation system**

Render:

Value:

- No contact with contaminated parts
- Bio-inspired design based on the human digestive system
- Tolerant of small objects

**System Evaluation**

| | | | | | Score | |
|---|---|---|---|---|---|---|
| Effort to lift the Lid | >40N | 30N | 20N | <10N | 2 | Quantitative |
| Pumping Volume (per lift) | <0.05l | 0.05 – 0.15l | 0.15 – 0.25l | >0.25l | 3 | Quantitative |
| Blockage Size | <1cm³ | 2cm³ | 3cm³ | >4cm³ | 2 | Quantitative |
| Complexity | >100 | 90 | 80 | <70 | 4 | Quantitative |
| Noise Level | >85dB | 75dB | 65dB | <55dB | 2 | Quantitative |
| System Integration | No Issues | Minor Issues | Issues | Major Issues | 3 | Qualitative |
| Serviceability | Simple | Relatively Simple | Average | Poor | 2 | Qualitative |
| Robustness | High | Medium | Average | Low | 1 | Qualitative |
| Efficiency | High | Medium | Average | Low | 2 | Qualitative |
| Dewatering | Fully | Partial | Minimal | No Effect | 4 | Qualitative |

Overall Score: 1

**Figure 32.** *The score matrix for the peristaltic pump*

### 6.10 Conclusion:

From gathering the results from the head to head testing and then forming these into a matrix for both the screw and peristaltic versions of the toilet. I conclude that the peristaltic toilet is the best version of the front-end toilet that we have currently. Due to it having not only the better qualitative score but also having the best quantitative score and therefore the best overall system score. It represents the toilet that gives the best user experience, ease of maintenance as well as overall robustness. It also requires the least amount of addition technologies in order to operate and function to full effect.

By conducting the head to head test, it has provided a system matrix for both the screw and peristaltic versions of the toilet. The matrix is setup so that future versions of the toilet can be tested following the same criteria and compared using a common scoring system. The test has also filled in a number of blank values such as force required from the user to open the lid, noise levels and blockage size to name a few. These measured values will be vital in the further development of the toilet going forward.

## 7 Discussion:

The aim of the project was to prove whether or not rapid prototyping provides an efficient route for the development and solution of critical competing technologies. Using the Nano membrane toilet as the case study to prove this by further developing an alternative version of the toilet transportation system, known as the PSPU. The need for the PSPU to be rapid developed into a fully working and optimised prototype, required rapid design and testing to be conducted upon it. Apply prior knowledge, gained through practical insights from previous work, of RP technologies and techniques to aid in prototyping. A developed and optimised solution for the PSPU was developed, which was then able to be tested in the head to head test. To demonstrate how RP was used in the development of the PSPU a chart, as shown in figure 34, was created. This shows each version of the PSPU from the original version up to the current version. It shows what was designed for and tested on each of the respective versions, with the successful designs for each sub system being carried forward to the next version.

As mentioned earlier the PSPU needed to be developed in a short space of time to allow for adequate testing to be conducted in the head to head test. The chart represents the work done in a 4-month period, as shown in the project time plan. Over the course of this development period, 164 individual custom components across 7 subsystems where designed, prototyped and tested. Without the use of RP techniques, which in this case was AM, this would not have been possible to have done. It would have also not been possible without using in house AM equipment, as out sourcing components would gain lead times pushing back the testing time.

Using the onsite facilities for RP including the FDM machines, MJP machine. Multiple iterative designs could be designed printed and tested. Some of the ideas generated for possible solutions to problems were able to be created and tested in a single. This allowed for any failures or non-functional designs to be quickly redeveloped or side lined. An example of this was the new design ratchet used within the gearbox of the PSPU. The design was created and the parts laser cut out in plastic assembled and tested within a day. This proved the ratchets operation was as expected, actually better than expected. So much so that it was not only used within the PSPU as it was designed, but also adopted as the new ratchet for the new HUT 3 prototype as well as the current and future discovery centre models. All of this impact was created from a simple laser cut prototype, designed and built in a single day. One thing to note is that some prior knowledge as to how RP technologies work would be recommended, mainly a knowledge of how each RP technique operates. To demonstrate the parts in figure 33 have both been created using different 3DP technologies. The one at the top was created using a standard consumer level FDM 3D printer, the other was created using a higher end consumer printer using MJP technology.

**Figure 33.** *PSPU pipe print comparison*

The part is a relatively complex geometry which if printed as one part on an FDM machine would require support material. Whereas it can be printed on the MJP printer as this uses dissolvable wax as the support material, it is both very costly in terms of financial cost and time. As can be seen in the image the top pipe is connected together using bolts this is due to the part being split into smaller section which could be printed without the need for support material. Comparing the times require to print each of the pipes the one printed on the MJP printer took around 15hrs, the one printed on the FDM printer took 4 hours. By simply split the part in to multiple sections meant that it could be implemented into the system faster solving a problem which could have led to a day of lost time. Someone who has some prior knowledge with RP would be able to identify ways in which a component can be made in a simple way that requires less time to be wasted between start and finishing a print.

Using RP techniques has been shown to reduce the time required to produce parts which can then be tested. There are however draw backs to using these processes such as surface finish of the parts, which in the case of FDM technologies have relatively rough texture due to the way in which the process works. Also to be noted are the need to add extra tolerance to allow for material shrinkage especially when using materials such as ABS. This can lead to mis-alignment of parts, such as the one shown early when the rotor was assembled. To compensate for this in the design each of the components created has been given a tolerance of around +0.2mm this allows for the material and the majority of the time ends up with the component being of the desired size. This is very much a minor annoyance in the consideration that parts are quickly produced and able to be tested in some case in a matter of hours. When it comes to using RP it is important to work with it in mind to make the manufacturing of the component as easy as possible, whilst maintaining the important parts of the design.

The decision to not use Finite element analysis, virtual prototyping or computer aided engineering, was due to the prototype being mainly a concept. At this stage in the development of the two prototypes it is a better use of time creating low fidelity prototypes to test concepts in the real world. Most of the systems on the prototype are still very much in development, FEA could be conducted on a part which in the real world doesn’t work in the system as it was thought to. This would end up cost time, when it could have been made into a physical prototype and tested and shown that it wouldn’t work before time was spent doing computer simulations. Another issue is that the techniques used to make the parts for the prototypes are not easily simulated. This is due to the process not creating a fully solid object, which would fail in a controllable way. Instead FDM technology for example creates a part that is made up of layers, when a force is applied in the direction of the layers the part will tend to split. If the force is applied in another direct the part will fail differently. It is this random failure that means they are extremely difficult, almost impossible to simulate on a computer. Hence why it was decided that for the purposes of building these prototypes no FEA, Virtual prototyping or computer aided engineering would take place.

Relating back to the literature review. Design fixation was an area that was researched. The reasoning behind this was to identify what design fixation actually is. Over the course of this research it has been noted that the screw is failing on many things that it was said to be able to do. For example it terms of it being a dewatering screw, if this is the case the screw should perform better in the tests where liquid is lower than the solids. It did however not perform well in the more solids to liquids part of the test, neither did it perform particularly well in the more water than solids tests. There is also the issue of requiring an average 67.1N of force to be applied by the user to lift the lid, the equivalent of lifting 6.8kg. This for a user would seem to be a chore in the end, which would inevitably lead to them leaving the lid open. This would mean no energy is stored in the spring so the screw doesn't turn and the tank fills up. If this became the user's behaviour when using the toilet then the product does function as intended. In future work this could be addressed, but the issue is far bigger. Design fixation as shown in the literature is described as "Blind adherence to a set of concepts or ideas will inevitably lead to the limiting of the outputted conceptual designs" (Jansson and Smith, 1991). The screw has been a part of the project since the first concept was generated. It was add without any testing to see if it would work and has meant that the design of the front-end has had to be designed around the screw. From what has been shown in the test the screw does not function as it was suggested it would, nor is it near to perform equally or better than the peristaltic version. In my opinion the screw concept is an example of a design fixation. It has limited the possible solutions to the problem, by needing to be incorporated into every version of the front-end. To me the peristaltic pump represents the opposite, it has been allowed to be developed with free reign to redesign every aspect of it. If a part on the system doesn't work it is redesigned. Which is why I believe it has ended with a far better system. Which requires less effort from the user to lift the lid, it is also able to purge the whole tank in less than the original intend lifts per day of 70.

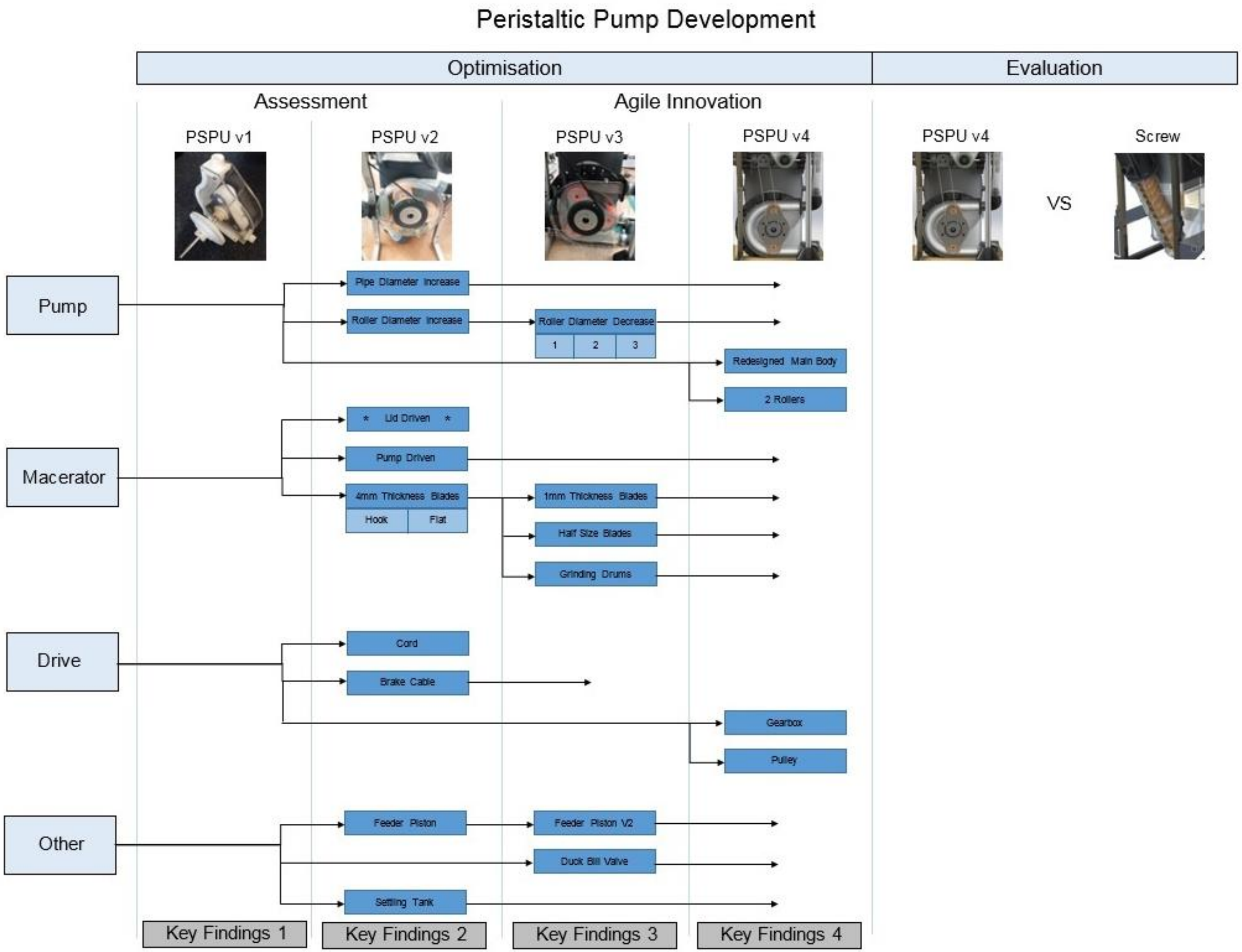



**Figure 34.** *The Peristaltic Pump development*

## 8 Conclusion:

To conclude through the use of RP a developed and optimised version of the peristaltic pump toilet has been created. This prototype along with the current screw version of the toilet, have been tested in a head to head comparison between them, to determine which is the better transportation system. The results of these tests have been implemented into a matrix system, which gives each a score based upon both quantitative and qualitative values. These matrix score cards can then be compared like for like, showing which of the systems is better. This information along with the scorecards can then be viewed by the wider team allowing them to make their own decisions based upon the results of the test. It has also been determined that RP does provide an efficient route for the development and solution of critical competing technologies. Demonstrated through the generation of a development chart, using the PSPU as the case study.

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