2018-07-06

Design for Maintainability in Developing Communities—A Case Study on the Uros Islands

Thomas Barlow

BYU ScholarsArchive Citation

Barlow, Thomas, "Design for Maintainability in Developing Communities—A Case Study on the Uros Islands" (2018). *Undergraduate Honors Theses*. 43.
https://scholarsarchive.byu.edu/studentpub_uht/43

Honors Thesis

DESIGN FOR MAINATINABILITY IN DEVELOPING COMMUNITIES—A CASE STUDY ON THE UROS ISLANDS

by
Thomas Barlow

Submitted to Brigham Young University in partial fulfillment
of graduation requirements for University Honors

Mechanical Engineering Department
Brigham Young University
August 2018

Advisor: Randy Lewis

Honors Coordinator: Brian Jensen

ABSTRACT

DESIGN FOR MAINATINABILITY IN DEVELOPING COMMUNITIES—A CASE STUDY ON THE UROS ISLANDS

Thomas Barlow

Mechanical Engineering Department

Bachelor of Science

Designing products for developing communities has exposed many of the underlying assumptions that engineers from developed nations have during the design process. There has been much written about these underlying assumptions in order to create a better framework for designing for developing communities. One unexplored, yet important area is the universality of common maintainability principles used in developed countries when designing products used in developing communities. Such principles include: simplicity, diagnosability, standardization of parts, modular subassemblies, minimizing assembly and disassembly parts, labeling components, increased life of moving parts, manuals, and simplifying tools needed for repairs [1]–[3]. The purpose of this research is to assess the universality of these maintainability principles for design in developing communities and determine any modifications or gaps that exist. A case study of a new low-cost water pump for Uros Islanders in Peru will be used to explore the practicality of the theory.

ACKNOWLEDGEMENTS

I would like to acknowledge the Ira A. Fulton College of Engineering, BD Medical, and the Weidman Center for Global Leadership for their support of the BYU Global Engineering Outreach Program and myself. I would also like to acknowledge the Coila family for their continued support in the Uros Islands and for my wife Renae who encouraged me to finish.

TABLE OF CONTENTS

LIST OF FIGURES

I. INTRODUCTION

Zero gravity, complete isolation, and zero-tolerance for failure have led NASA to create its own stricter standards for maintenance requirements of equipment in space, called NASA Standard 3001. These standards modify common Design for Maintainability Principles (DFMAIN) to create more specific requirements tailored to the needs of space exploration. NASA's modifications illustrate how certain DFMAIN principles have been customized in different contexts. Another context that this paper will focus on are low-resource settings (LRSs). Quite often engineers from developed countries, when designing for LRSs, forget maintainability principles, focus on only a few, or apply them incorrectly. Such modification of DFMAIN, for developing communities, should consider all the relevant principles and understand them in the context of their unique barriers and constraints. These modifications could help guide engineers to select the best design, improve affordability, address ease of repair, and remove incorrect assumptions when designing devices for developing communities.

Many products for developing communities fail because of incorrect assumptions [4]. For example, an engineer may assume that the incentive and resources exist to repair a broken pump when in fact there is no financial and little social incentive for these repairs. On the Uros Islands, the natives would rather return to using buckets than try to fix their pumps. Also, engineers may incorrectly assume that parts used for product maintenance and repair will be available locally. But, parts may be inaccessible due to lack of transportation, cost, change of suppliers, or knowledge. Wrong assumptions may result in products that are costly and hard to repair once broken—thus creating unsustainable technologies. These assumptions could be refined by better understanding how basic design principles vary between developed and developing countries. Maintainability principles are particularly important to understand and have not been sufficiently studied. As Aranda found from literature and interviews, affordability was the most commonly mentioned technical challenge in LRSs. Availability of spare parts, a common DFMAIN principle, was second [5]. By improved understanding and application, ease of maintenance can be improved and will reduce the lifetime cost of a product as well as maximize its benefit [6]. Maintainability is only one technical aspect of the complex design process, but it is especially important in LRSs where resources are scarce and higher relative opportunity cost . Hand pumps have been a particular focus for design in developing communities and there has been effort to apply maintainability principles.

The UNDP-World Bank developed an informal standard for hand pumps known as Village Level Operation and Maintenance Management (VLOM) in the 1980's. This was widely accepted for many decades as a standard for hand pump design and was implemented in many developing communities [7]. VLOM status was given to pumps that could be locally manufactured, had available spare parts, were robust and reliable, were cost effective, and were modular. These are all principles that are accepted in literature and industry as methods for improving the ease of maintenance of a product. However, VLOM has not proven to be as effective at creating maintainable pumps as first expected due to a narrow technical focus on maintenance as well as underperformance of the technologies [8], [9].

While community involvement is essential for maintainable technology, the focus of this paper is on assessing the universality of DFMAIN principles in LRSs to help reduce the failure rates of products designed for developing communities. This paper uses a water pump case study as a means of assessing these principles.

II. LITERATURE SEARCH

A literature search was first conducted to create a concise but comprehensive list of maintainability principles used in developed regions [2], [3], [6], [10]–[12]. These were used to create a list of DFMAIN principles that were then used in the hand pump case study. This list is discussed below, and includes principles such as simplicity, availability of spare parts, modularity, and availability of tools. The principles were also used for assessment of designs for developing communities to understand the universality of each principle.

Because the literature lacks any comprehensive work on maintainability principles applied in developing communities, individual examples are assessed in this paper. These examples followed some or all of these design principles to create a device that was easy to maintain. Hand pumps were specifically included in the search, because the case study was to design one. Some of these pumps included the Afridev, EMAS, and Tara pumps, which were used to determine the relevance of common DFMAIN principles in the context of LRSs.

DFMAIN principles may also be dependent on product type (see Frappier et al., 1994), so other types of devices besides pumps were considered while assessing the universality of the maintenance principles. Limitation of lack of proprietary access to certain designs meant they couldn’t be included in this study. Examples include, the Jaipur knee and the FireFly phototherapy machine. Two other types of devices were assessed—OLPC’s XO laptop and the NeoNurture Incubator. Both of these devices were considered failures and help demonstrate important principles to be considered in LRSs [13]. These devices provide important lessons on maintainability principles. These products were included based on their explicit focus on maintenance as a design requirement.

III. MAINTAINABILITY PRINCIPLES

A list of DFMAIN principles was created from both international standards and those presented in research [2], [3], [6], [10]–[12]. Short definitions are presented below, taken largely from Tjiparuro. Not every principle is applicable to every product, but the list is fairly comprehensive, excluding software.

A. DFMAIN Principles

Simplicity—Reduced number of parts and assemblies including redundant components.

Accessibility—Easy access for visual and manipulative tasks, i.e., for inspection, adjustment, repair, etc.

Diagnosability—Fault detection, localization and isolation in the quickest possible time.

Parts/Components—Physics of parts and components such as weight and size.

Availability of tools and equipment—Suitable standard hand tools available.

Disassembly/assembly—Easy and quick opening/fastening of mating parts or components.

Modularization—Repair/Replacement of functional units quickly to restore overall function of system.

Personnel (including ergonomics)—Maintenance tasks are designed to the skill and motivation level of an average technician. Tasks should be such that no more than two technicians are required for accomplishment.

Documentation—Availability of troubleshooting and maintenance procedures, checklists, and instructions, etc.

Standardization—Interchangeability is possible between mating components when replacing a faulty item, i.e., no physical rework required to achieve a functioning system. Few adjustments are needed to achieve proper functioning. The types of parts are minimized.

Tribo-concepts/Serviceability—Features that promote the retention of the intended condition, that is, wear resistance, life time lubrication, long-life lubrication and surface coating.

Safety—Hazardous-free environment for maintenance work, i.e., no proximity to high voltage lines, no gaseous leakages, moderate temperature changes, etc.

Testability—Characteristics that allow the status (operable, inoperable, or degraded) of an item to be determined

Availability of spares—Availability of quality spares at affordable cost.

System Environment—Enough illumination, lighting, protection against dampness, cold, heat, etc.

Identification—Adequate labeling, engraving and marking of parts and critical points.

Reliability—Low failure rates of parts, components, and assemblies in the system. Parts, components and assemblies' failure rates should be known, and the corresponding modes of failure (FMEA).

Tools and test equipment—Minimum number of required tools and supporting equipment and ease of use, e.g. spanners, lifting machines, over head cranes, etc.

Operation / Mission profile—Appropriate redundancy for critical device components, such as in continuous operation systems.

Motivation—Including the motivation of the personnel and the owner/user. This extends to the motivation to ask for repairs, learn how to repair, and seek help.

These principles above were compiled from a few sources in literature as seen in the following table. While there were other sources that contained these principles, they did not contribute any unique principles and were therefore excluded from the paper for simplicity.

Table 1: Origin of maintainability principles as found in the literature

DFMAIN Principle Used	**Authors**	**Comments**
Simplicity	Tjiparuro [2], Wani [3]	
Accessibility	Tjiparuro [2], Wani [3], Blanchard [6]	
Diagnosability	Tjiparuro [2], Wani [3]	
Parts/Components	Tjiparuro [2], Blanchard [6]	
Availability of tools and equipment	Tjiparuro [2]	Modification of spares procurement which expands to tools
Disassembly/assembly	Wani [3]	Tjiparuro uses a more narrow principle and so Wani's was used
Modularization	Tjiparuro [2], Wani [3],	
Personnel (including ergonomics)	Tjiparuro [2], Wani [3], Blanchard [6]	Combined all of related specifics into one principle so as to view the user and repairer more holistically depending on the product
Documentation	Tjiparuro [2], Wani [3]	
Standardization	Tjiparuro [2], Wani [3], Blanchard [6]	
Tribo-concepts / Serviceability	Tjiparuro [2], Wani [3], Blanchard [6]	Modified by combining all three variations between the authors
Safety	Tjiparuro [2], Blanchard [6]	
Testability	Tjiparuro [2], Blanchard [6]	
Availability of spares	Tjiparuro [2], Blanchard [6]	

System Environment	Tjiparuro [2], Wani [3], Blanchard [6]	
Identification	Tjiparuro [2], Wani [3], Blanchard [6]	
Reliability	Tjiparuro [2], Blanchard [6]	
Tools and test equipment	Tjiparuro [2], Wani [3], Blanchard [6]	
Operation / Mission profile	Tjiparuro [2]	
Motivation		Added after experience with the case study. Separated out from "Personnel" due to importance and how it can be assessed and determined during the design process
Not Used		
Anthropology	Tjiparuro [2]	Combined into Personnel
Software	Blanchard [6]	Disregarded in this paper as there are already modified standards and guidelines for software maintainability
Physiological	Tjiparuro [2]	Combined into Personnel
Psychological	Tjiparuro [2]	Combined into Personnel
Adjustments	Blanchard [6]	Included in Serviceability
Calibration requirements	Blanchard [6]	Combined into testability
Reconsidering		
Panel Displays / Controls	Blanchard [6]	Was combined into testability by Tjiparuro but may better be reclassified as **usability,** as discussed later

B. Lessons from Literature/Products:

Tara Pump— Pumps have been designed and used in LRSs for many years and their life cycle is well understood. The Tara pump is a direct action hand pump, meaning the user lifts the piston rod and does not use any lever. The pump has a simple design, which means it is inherently easier to build, maintain, and repair than more complex pumps. Compared with deep well pumps like the Afridev and India Mark II, the Tara has no lever which puts less stress on the pump rods, reduces parts, removes the fulcrum and bearings which often break, and removes the heavy pump stand which can require equipment for moving [14]. The Tara pump shows how simplicity and usability can improve the pumps maintainability and reliability.

Pumps in LRSs also show the importance of another principle—availability of spare parts. A conflict in Darfur Sudan intensified the lack of spare parts and tools when travel between cities became unsafe. This made it very difficult to repair the pumps with outside spares, so many of the broken pumps were cannibalized to repair and maintain a few [15]. This emphasized the need for universality of available spare parts. This example, and others were used to assess the applicability of DFMAIN principles in developing communities.

XO Laptop— OLPC's XO laptop was designed as part of the movement to give every child in LRSs a laptop. These laptops were originally designed to be extremely durable, repairable by the children who would use them, and have available spare parts. The improved durability would come from having no moving internal parts, a sealed case, protected keyboard, heavy duty case, and covers for all external ports. Extra screws for the case and screen were even incorporated into the handle of the laptop, which is where the child was supposed to carry it, to help with any lost bolts during reassembly. The actual use of the laptop however quickly resulted in failed components, most notably the screen [16], [17]. Other parts that failed included the chargers and keypads. Unanticipated uses of the laptop included children running with the screens open so they could use their camera, which was front facing, or walking with the laptop open so music could be played, which was only possible with the laptop open. This resulted in drops and broken screens. As Steeves and Kwami point out, the belief of its superior durability may have in fact led the children to use it much more roughly than if durability had not been emphasized. Besides unforeseen use, cost played an important factor in the ability to repair the broken devices.

NeoNurture— Various companies and organizations praised the NeoNurture Incubator for its innovative design when it was first introduced. It was designed with reliability and maintenance in mind. Its main virtue was that it was partially made from car parts, which are readily available in many developing communities [18]. The idea was not only that the parts could be easily replaced if broken, but that local mechanics could also be easily trained on how it worked and fix it. Designers hoped to tap into existing resources. But the device failed to move beyond a prototype. According to the designer and owner of the device, it was because it did not look or feel like a real medical device to the potential customers [19], [20]. While the device never was put into service, and it is hard to know how it would have performed technically over time, it demonstrates that despite ease of access to spare parts other technical issues arise.

C. Universality of the principles:

Using information from both the literature and this case study, the maintainability principles were divided into two groups; universal and context dependent. The universal principles are applicable in developed regions as well as developing regions and should be applied when designing any sustainable product. Those without any explanation (see below) are deemed adequate for both developed and developing contexts with no further explanation necessary. The context dependent principles require modifications when applied in low-resource settings.

Universal Principles:

- Simplicity
- Accessibility
- Diagnosability
- Disassembly/assembly
- Modularization: This is often in direct conflict with cost and will likely have to be less modular in order to meet the common market requirement of cost seen in an LRS.
- Safety
- Testability
- System Environment
- Identification: As mentioned below in "Documentation", identification could be expanded to include more instructions and not just identification of parts. This could help when manuals or other resources might easily be lost or Internet access may be limited. If this is the case, markings on parts should also be placed in an easy-to-see position with markings that will not be obscured if a piece breaks.
- Tools and test equipment
- Operation / mission profile
- Motivation

Context Dependent Principles:

The following principles need modifications when applied to an LRS.

- Standardization
- Personnel including ergonomics

- Parts / components
- Availability of spares
- Tribo-concepts / Serviceability
- Documentation
- Availability of tools and equipment
- Reliability

D. Modifications to the Principles:

Standardization: Standardized parts should be locally available. In developed countries standardized parts require correct tolerances and dimensioning for fitting easily with other parts when being replaced. This is not always economically feasible in LRS. Tolerances beyond manufacturer's specifications should be expected and designed for. Critical components should not be dependent on tight tolerances if local manufacturers will be unlikely to comply. Also, some standardized parts will have various manufacturers with varying quality and specifications. Because front end users, who are highly sensitive to cost, could often carry out maintenance, buying patterns should be considered when choosing standardized parts. For example, if there are two parts that are the 'same' by label but vary in quality, tolerance, etc. the cheapest part will likely be purchased even if detailed instructions require otherwise.

Standardized parts may also not be desirable as some standardized parts, such as the plastic bolt used in the case study, may be more difficult to obtain and use than a custom wooden or plastic pin. Some custom parts, depending on the skills and familiarity of the locals, may easier to manufacture on site than to source through rare channels.

One example of a device that met ease of modification of “standardized” parts in an LRS context was the NeoNurture Incubator. As discussed by Janzar the NeoNurture primarily used car parts for failure prone components that could be found in developing communities [18]. This would allow mechanics to easily fix the medical equipment because of their familiarity with the parts and design, and was partially tested during the development phase. Designing for other readily available parts, which may not be found in a catalogue, could allow for improved maintainability and sustainability.

Personnel, including ergonomics: Maintenance personnel are usually not going to be full-time technicians. First-line maintenance should be more fully considered when designing for developing communities. Other possible personnel are self-trained technician handy-men. These might have a shop where they fix a variety of products. By designing a device that is similar to common devices in the region, more skilled workers could also be considered part of the maintenance plan, decreasing the training required for teaching maintenance. Markings and symbols should be used that are understandable for trained and self-trained technicians. Personnel should also be available in a timely manner. According to Carter [21], available transportation for maintenance work may determine if a water system will be maintained.

Parts / components: Decreasing specificity of likely to be replaced parts, or decreasing the required tolerances of a replaceable part, or increasing the ability to interchange parts with a variety of other parts, increases the likelihood it can be repaired. For example, Will any type of PVC connector do, or is a specific type needed? Is a glass marble required, or will any ball of a certain size work? If foreign parts are used, then distribution, transportation, and cost become very important.

Availability of spares: Consider including spares directly into the design such as, extra buttons that are sewn into a dress shirt, a spare tire, XO laptop with extra screws in the handle, etc.

Tribo-concepts / Serviceability: While reducing wear through lubrication will improve maintainability universally, it has been observed that this type of routine servicing of parts may be unlikely for many products. Because of the recurring cost, often without any of the financial incentives a technician has in developed regions, it should be assumed that routine maintenance will not occur unless a plan is already in place. It may be better to use self-lubricating parts and/or reduce the number of parts that need to be lubricated.

Documentation: Also consider having instruction videos (if internet is available). Otherwise, manuals may be built directly into the product. This is closely tied to labeling or identification. With the XO laptops, extensive documentation was available online, but most laptops that broke were never fixed. This could due to a variety of reasons, but a laptop with a broken screen makes it impossible to look up the documentation on how to fix that screen.

Availability of tools and equipment: Do not assume standardized tools are available. If a specific tool is necessary, consider incorporating that tool into the product. Understanding of available tools for performing tasks, including unconventional tools, should be determined early in the design process. For example, a hot nail can be used to create holes in plastic instead of a drill.

Reliability: While reliability is obviously universally applicable in both developed and developing regions, it is important to mention **usability** as an aspect of reliability and perhaps as its own principle. By making the design easy to use, easy to obtain the desired objective, and hard to misuse, failures will decrease. In the example of the XO laptop, the misuse, according to the designers, was a common use and led to laptop failures. If this knowledge had been obtained during the design process measures could have been taken to ensure the laptop was not used in this way. Another example why usability may be its own principle is the Tara pump. Because the usability of the design was changed to a less ergonomic T-shaped direct action motion, the forces on the piston rod were reduced and changed the forces/environment that the pump saw. This allowed for a more reliable and robust pump. This shows how usability can be used to change a product so that it lasts longer and requires less maintenance.

Also, hard to obtain parts should be overdesigned to the point that they are very unlikely to break. Many devices designed for developing communities often are foreign sourced or produced. These parts are often hard for maintenance personnel to buy locally and should be built for durability and cost. A device that breaks down more often but is quicker to fix could be more reliable than a device that lasts longer but takes longer to fix.

IV. UROS WATER PUMP CASE STUDY

The Brigham Young University Global Engineering Outreach class has designed and implemented projects, processes, and products for developing communities for over a decade. One of the projects was a water pump for the Uros Community near Puno, Peru on Lake Titicaca. The Uros people have lived on Lake Titicaca for over 400 years where they have built man-made floating islands as their homes. These islands are made from totora plants, using both the roots and the reeds, and permit families to live on the lake. Though far from shore their islands are in the midst of the totora reeds and the approximately one hundred islands line the edge of a reed-made channel. The water in the channel is both a major thoroughfare for boats as well as a source of drinking water. Most islanders we met currently retrieve water from the middle of the channel early in the morning with buckets in order to obtain cleaner water before boats stir it up.

The lake has become more and more contaminated. Many Uros people are moving to Puno at night where they can get clean water. Many of these people only work on the islands in the day, to sell to tourists and to maintain their islands. Those who have chosen to stay, in order to maintain their cultural heritage, struggle to find clean water. Some locals specifically associate their current health issues with the water they drink.

In 2016 a simple suction pump was designed and implemented on the Uros

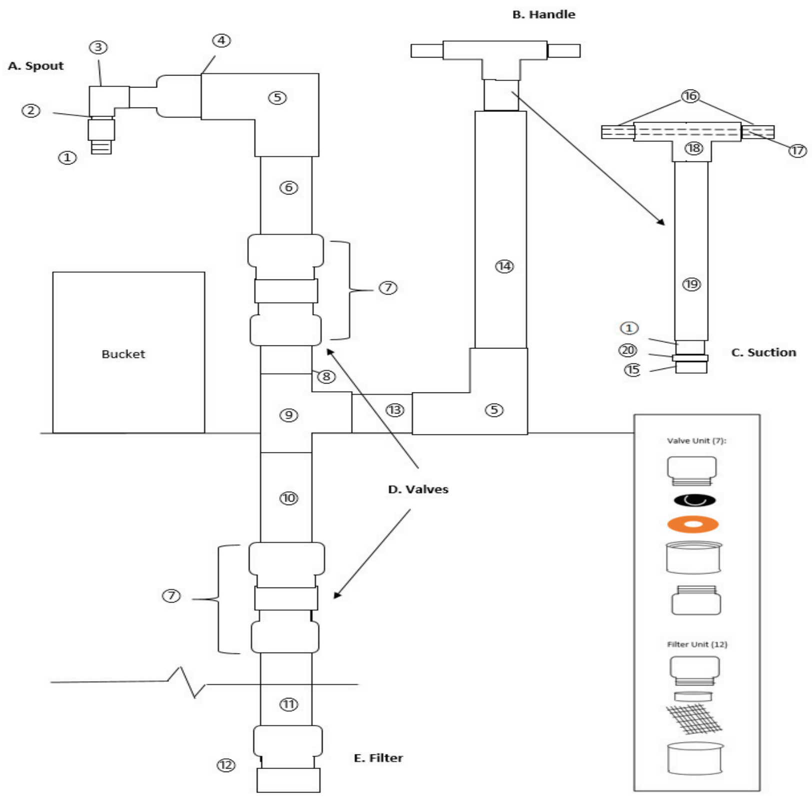


Figure 1: BYU GEO suction pump design from 2016. Used custom valves that are seen in the bottom right of the figure.

Islands by BYU GEO students (Figure 1). Many of the families that owned these pumps mentioned, without prompt, that their health had improved since receiving the pump. In May of 2018 a Quanti-Tray method was used to test for E. Coli in water samples. The tests showed that the water from the surface had three times as much *E. Coli* as water pumped from a 2 meter inlet below the islands (see Table 2: Quanti-tray method for Coliform and E. Coli on one island in Lake Titicaca). While this proves the islanders' self-assessment of the pumped water being cleaner, the coliform and *E. Coli* count were still well above the EPA and Peru Health recommendation of zero in all samples [22], [23].

Table 2: Quanti-tray method for Coliform and E. Coli on one island in Lake Titicaca

MPNs	Total Coliforms	*E. Coli*
Unfiltered surface water	=>2419.6	30.1
Unfiltered pump water	=>2419.6	8.6

The pumps from 2016 were providing cleaner water, except that many of them had broken and were not being maintained by the fall of 2017. In 2018 a group of students, including myself, worked on designing a new and improved water pump for individual families on these islands. A key design requirement was improving the maintainability and reparability of these new pumps. The 2016 pump was a direct action suction pump with custom flap valves. The body of the pump was built from PVC pipe and suction was produced by using a handmade custom leather seal. The valves were also custom valves created from local materials. There were 12 to 14 pumps installed in 2016.

In the summer of 2017 a BYU Project Evaluation Assessment Team (PEAT) visited the Uros Islands to assess the use and success of the pumps. From this onsite evaluation as well as phone calls to pump owners, the pump failures were better understood. The most common failures were the leather seal and valves. Talking with owners of these pumps revealed that the primary problem with using leather seals is that constant drying and wetting of leather causes it to deteriorate over time. Other problems were the need to prime the pump (remove the suction piston and pour water down the tube), and valve malfunction when the rubber flap was sucked through the hole it covered. The reason for any successful maintenance of the pump was due to high motivation of certain individuals to fix the failures. A major goal of the new pump was to improve maintainability by eliminating the leather seal and improving the valve design to design for those not currently fixing their pumps.

The new 2018 design (see Figure 2) incorporated certain DFMAIN principles while handling tradeoffs, customer requirements, and other design principles. The final design incorporated various maintainability principles while also researching and working with locals to decide the feasibility and effectiveness of different designs.

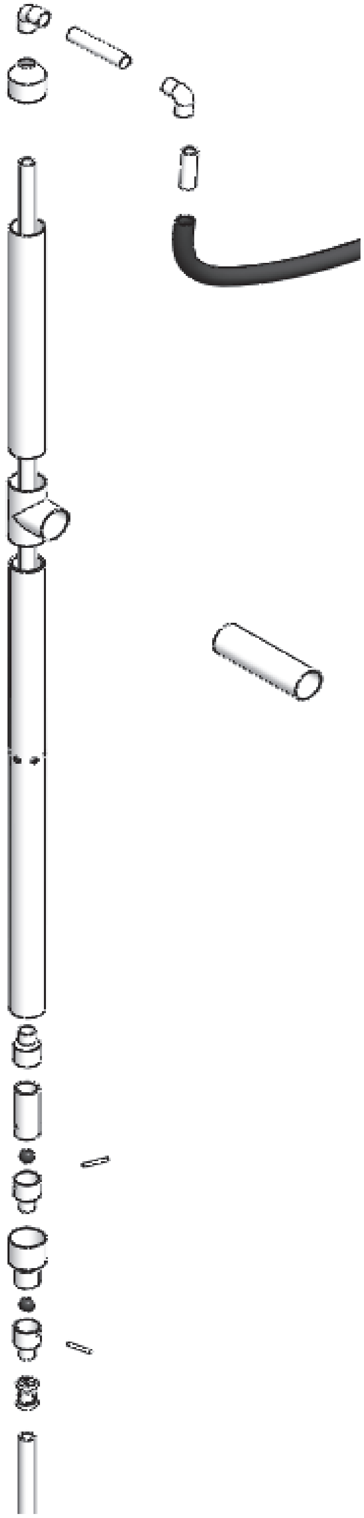


Figure 2: Exploded view of 2018 GEO pump.

The final pump design, as seen in Figure

3, was a direct action lift pump in a single casing similar to deep well pumps. The pump design was very similar to the EMAS pump first designed by Wolfgang Buchner for use in Bolivia. While the functionality and design principles were very similar, parts were added or removed in order to decrease the complexity of manufacturing and maintain the pump. The following maintainability principles were used during the 2018 pump design process.

Figure 3: Direct action lift pump being installed on the Uros Islands

A. Applied DFMAIN Principles

Simplicity: The 2018 pump was continually simplified throughout the design process to reduce parts, assembly steps, steps in the repair, etc. One major improvement was to remove seen in removing all custom made parts, except simple modifications of a plastic bolt that is cut with a hacksaw and a few cuts of the PVC pipes. All other parts on the pump can be assembled after buying them from a local store. This simplicity made it extremely easy to teach locals how to build or repair the pump.

Accessibility: While the EMAS pump works very well and has thousands in use in South America, it involves a variety of steps in making the pump that require heating PVC tubes in order to fit them together with other pieces. For example, the valves permanently fit together and cannot be bought or made locally if they break. While this makes an easy-to-assemble modular design, it does not allow for easy repair. Our 2018 pump allowed for easy accessibility to the piston and foot valve and any moving parts by removing a single plastic bolt.

Standardization: One goal of the 2018 case study design team was to use all local standardized parts in order to reduce complexity and to increase the maintainability of the pumps. This was mostly achieved since a few parts were not sourced directly from Puno. The standardization helped improve the assembly process as well as the ability for untrained owners to service their own pumps. However, some of the standardized parts were not within standards or only sold by one supplier. This will make it hard for repairing the parts later if the supplier stops selling or the owners assume they can buy elsewhere.

Standardized parts may also not be desirable as some standardized parts, such as the plastic bolt used in our design, may be more difficult to obtain and use than a custom wooden or plastic pin.

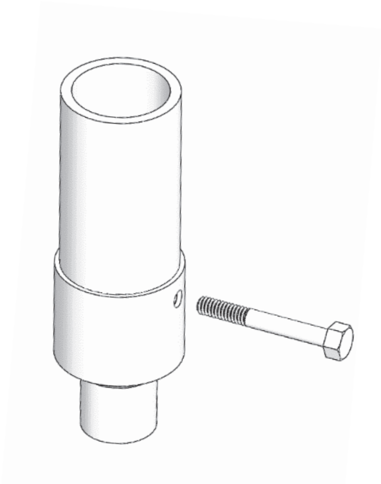


Figure 4: CAD model of a partially assembled piston valve. The bolt both connects the tubing and traps the marble.

Disassembly/assembly: The manufacture and assembly of the pumps was performed in under an hour once the parts were all gathered. The steps for assembly decreased as standardization and simplicity improved. The disassembly of the valves could be done in three simple steps, which was also consciously decided as design options were assessed. The ‘seal’ or the plastic reducer / ball valve could be diagnosed for failure in one step by removing the outlet pipe which is attached to the piston.

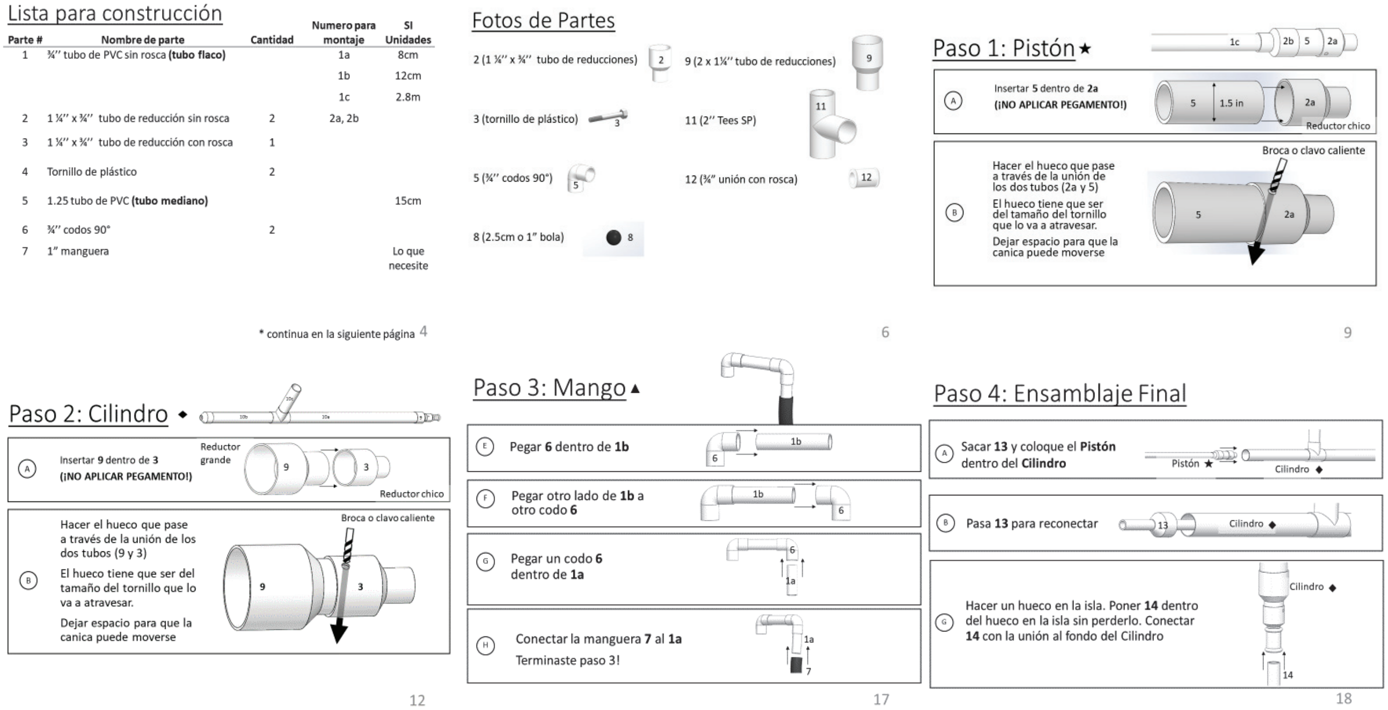
Modularization: Modularization was increasingly exchanged for simplicity as the pump design evolved. A few changes to the end design were the threaded inlet pipe (instead of gluing a press fit) and the replaceable valves. Other parts used for modularity were later removed to reduce cost. The threaded inlet pipe was used for both improved installation as well as potential maintenance of a broken inlet pipe. Many of the islanders mentioned fears of their islands losing anchor in a storm and the inlet pipes breaking as the island shifted. The threaded pipe would thus allow for easy repair of the inlet pipe.

Parts/components: The threaded inlet pipe was intentionally chosen not only for reparability but also to allow for easier installation of the pump. The pump was initially installed with all the parts attached. Because the ¾" inlet was 5 meters long and the pump cylinder was on top, the piping was inserted in the hole in the island at a considerable angle (~30-40 degrees). The PVC purchased in Puno was brittle and inserting the pump into the hole in the island resulted in a broken inlet pipe. By using a threaded inlet pipe, this could be avoided by inserting and remove the pieces individually.

Reliability: The major causes for failure in the 2016 pump, were the seal and valves. Because of the high failure rate of seals, they were removed from the 2018 model. Centrifugal pumps, or multiple sealed pumps (like a rope pump) were evaluated. In the end, the design removed the seals by using a tight-fitting reducer inside of a PVC tube. An FMEA was created and failure modes were designed to reduce frequency of occurrence. An initial 10,000 pump cycles were done with the design to assess its durability, and no significant wear was seen. The time frame of the project did not allow for more complete testing of the pump, but initial assessment was that this should last the desired 3 years.

Tools: A hacksaw and a device for making holes (a hot nail was used in the case study) were the only tools needed for building the pumps. Necessary tools were continually reduced and removed as the design progressed and made assembling very easy. Repair of the pump would also only need these two tools, which are available to the Uros Community. Many of the repairs would need only one commonly available tool at most.

Documentation: Documentation was emphasized even in our short design cycle, but proved to be impossible to complete at implementation since the design changed when the team arrived in Peru. The documentation has since been updated and delivered electronically to a few of the pump owners and the community representative who we worked with. As of June 2018, no assessment has been made of the success of this documentation.



Lista para construcción

Parte #	Nombre de parte	Cantidad	Numero para montaje	SI Unidades
1	¾'' tubo de PVC sin rosca **(tubo flaco)**		1a	8cm
			1b	12cm
			1c	2.8m
2	1 ¼'' x ¾'' tubo de reducción sin rosca	2	2a, 2b	
3	1 ¼'' x ¾'' tubo de reducción con rosca	1		
4	Tornillo de plástico	2		
5	1.25 tubo de PVC **(tubo mediano)**			15cm
6	¾'' codos 90°	2		
7	1" manguera			Lo que necesite

* continua en la siguiente página

Fotos de Partes

2 (1 ¼'' x ¾'' tubo de reducciones)
9 (2 x 1¼'' tubo de reducciones)
3 (tornillo de plástico)
11 (2'' Tees SP)
5 (¾'' codos 90°)
12 (¾" unión con rosca)
8 (2.5cm o 1" bola)

Paso 1: Pistón ★

Ⓐ Insertar **5** dentro de **2a**
(¡NO APLICAR PEGAMENTO!)

Ⓑ Hacer el hueco que pase a través de la unión de los dos tubos (2a y 5)
El hueco tiene que ser del tamaño del tornillo que lo va a atravesar.
Dejar espacio para que la canica puede moverse

Paso 2: Cilindro ◆

Ⓐ Insertar **9** dentro de **3**
(¡NO APLICAR PEGAMENTO!)

Ⓑ Hacer el hueco que pase a través de la unión de los dos tubos (9 y 3)
El hueco tiene que ser del tamaño del tornillo que lo va a atravesar.
Dejar espacio para que la canica puede moverse

Paso 3: Mango ▲

Ⓔ Pegar **6** dentro de **1b**

Ⓕ Pegar otro lado de **1b** a otro codo **6**

Ⓖ Pegar un codo **6** dentro de **1a**

Ⓗ Conectar la manguera **7** al **1a**
Terminaste paso 3!

Paso 4: Ensamblaje Final

Ⓐ Sacar **13** y coloque el **Pistón** dentro del **Cilindro**

Ⓑ Pasa **13** para reconectar

Ⓖ Hacer un hueco en la isla. Poner **14** dentro del hueco en la isla sin perderlo. Conectar **14** con la unión al fondo del Cilindro

Figure 5: Samples from the documentation created for the pump in the case study

Personnel: The personnel were carefully considered when designing the pump. All construction and maintenance steps were simplified so that the owners of the pumps could also maintain and construct their own pumps. While time constraints resulted in only a few people learning how to build and maintain the pumps, instructions are being provided for others.

B. Future Improvements / Modifications:

All of the design principles above were discussed prior to implementation, and were assumed to be adequate for the situation. Once the design was implemented other design considerations arose as the design was modified. The design principles needed to be adapted. All of these modifications are discussed in the applicability section above and some will be explained in context here.

Standardization: The assumption of using standardized parts is that these parts are easy to find, cost effective, and within tolerances. However, this may not be the case in developing communities. For example, PVC tubing may be considered a standardized part in both the US and in Peru, but different tubes may have tolerances outside of those required by industry standard. Also, certain standardized parts may be more difficult to find in certain parts of the country. For example, in Puno, pressure PVC pipes (tubos para presión) were very difficult to find, even though we found them easily in Cajamarca, Peru.

Parts: As mentioned in the sections above a consideration when choosing parts is to use a design that could incorporate a variety of parts, or a part that could vary in tolerances. By decreasing the required specificity of the part, the design also might be more transferable between countries when cost restraints require local production and materials.

Labeling/Documentation: Labeling of the parts was not fully considered during the design process. In hindsight, it seems labeling could potentially improve maintainability of the pumps. In this case, because documentation is difficult to obtain for many of the owners, who are also the ‘technicians,’ building the documentation *into* the pump would have been most helpful for them. For example, labeling or engraving very concise instructions into the valve could help a few families that live without access to Internet. The labeling could have replaced the documentation that will likely be lost, misplaced, or destroyed.

V. CONCLUSION

Almost all product designs have a goal of increasing reliability while decreasing the cost of maintainability. The importance of this goal varies across products but is almost always important in LRSs. This importance is most often directly related to the higher cost constraint seen in this context. Improving maintainability of products for LRSs thus impacts sustainability even more in this context than in developed regions. As both the literature and the case study show, there are slight modifications and additional considerations that should be applied to traditional maintainability principles.

By better understanding the context, people, and environment where the product will be used, the designer will be able to improve the sustainability of their product. The assumptions of the engineer will not be the only guide to designing more maintainable and repairable products for the developing communities. Engineers should consider more customized principles in the context of their particular setting as not all DFMAIN principles should be applied the same way for developed and developing communities. Even further, developing communities may vary widely and DFMAIN principles will likely need to be applied separately for each particular case. For example, the case study in the Uros Islands was unique as the community is close to a fairly developed market in the cities Puno and Juliaca. This is a very different context from the pumps mentioned in war torn Darfur Sudan. While this paper proposes some maintainability modifications, further work should be done in refining and understanding customized Design for Maintainability principles for low-resource settings.

REFERENCES

[1] L. Chen and J. Cai, “Using Vector Projection Method to evaluate maintainability of mechanical system in design review,” *Reliab. Eng. Syst. Saf.*, vol. 81, no. 2, pp. 147–154, Aug. 2003.

[2] Z. Tjiparuro and G. Thompson, “Review of maintainability design principles and their application to conceptual design,” *Proc. Inst. Mech. Eng. Part E J. Process Mech. Eng.*, vol. 218, no. 2, pp. 103–113, May 2004.

[3] M. F. Wani and O. P. Gandhi, “Development of maintainability index for mechanical systems,” *Reliab. Eng. Syst. Saf.*, vol. 65, no. 3, pp. 259–270, Sep. 1999.

[4] A. E. Wood and C. A. Mattson, “Design for the Developing World: Common Pitfalls and How to Avoid Them,” *J. Mech. Des.*, vol. 138, no. 3, p. 031101, Mar. 2016.

[5] C. Aranda Jan, S. Jagtap, and J. Moultrie, “Towards A Framework for Holistic Contextual Design for Low-Resource Settings,” Dec. 2016.

[6] B. S. Blanchard, D. C. Verma, D. Verma, and E. L. Peterson, *Maintainability: A Key to Effective Serviceability and Maintenance Management*. Wiley, 1995.

[7] J. M. Reynolds, “Handpumps : toward a sustainable technology - research and development during the water supply and sanitation decade,” The World Bank, 11426, Oct. 1992.

[8] J. Colin and D. A. Cotton, *Task Management & Quality Assurance by:* 1999.

[9] J. MacArthur, “Handpump Standardisation in Sub-Saharan Africa,” *RWSN Publ.*, vol. 1, 2015.

[10] K. T. Al-Sarayreh, A. Abran, and J. J. Cuadrado-Gallego, “A standards-based model of system maintainability requirements,” *J. Softw. Evol. Process*, vol. 25, no. 5, pp. 459–505, Mar. 2012.

[11] M. Frappier, S. Matwin, and A. Mili, *Maintainability: Factors and Criteria*. 1994.

[12] R. Lewis, “NASA Standard 3001,” *NASA*, 04-Mar-2015. [Online]. Available: http://www.nasa.gov/hhp/standards. [Accessed: 14-Jun-2018].

[13] D. W. Beuermann, J. Cristia, S. Cueto, O. Malamud, and Y. Cruz-Aguayo, “One Laptop per Child at Home: Short-Term Impacts from a Randomized Experiment in Peru,” *Am. Econ. J. Appl. Econ.*, vol. 7, no. 2, pp. 53–80, Apr. 2015.

[14] B. J. Kjellerup, “The Tara handpump : the birth of a star,” The World Bank, 11436, Nov. 1989.

[15] S. Esposto, “The sustainability of applied technologies for water supply in developing countries,” *Technol. Soc.*, vol. 31, no. 3, pp. 257–262, Aug. 2009.

[16] D. K. Rosner and M. Ames, “Designing for Repair?: Infrastructures and Materialities of Breakdown,” in *Proceedings of the 17th ACM Conference on Computer Supported Cooperative Work & Social Computing*, New York, NY, USA, 2014, pp. 319–331.

[17] H. L. Steeves and J. Kwami, “Interrogating Gender Divides in Technology for Education and Development: the Case of the One Laptop per Child Project in Ghana,” *Stud. Comp. Int. Dev.*, vol. 52, no. 2, pp. 174–192, Jun. 2017.

[18] C. L. Janzer and L. S. Weinstein, “Social Design and Neocolonialism,” *Des. Cult.*, vol. 6, no. 3, pp. 327–343, Nov. 2014.

[19] "Could an infant-saving product prove the death of human-centred design?" *2018 NEXT Design Awards*. [Online]. Available: http://drivenxdesign.com/next17/news_details.asp?AssetId=47280. [Accessed: 13-Jun-2018].

[20] T. Prestero, "The Neonurture," *sciencegallery.com*, 28-Jan-2014. [Online]. Available: https://dublin.sciencegallery.com/failbetter/neonurture. [Accessed: 13-Jun-2018].

[21] R. C. Carter, S. F. Tyrrel, and P. Howsam, "The Impact and Sustainability of Community Water Supply and Sanitation Programmes in Developing Countries," *Water Environ. J.*, vol. 13, no. 4, pp. 292–296.

[22] "Calidad del agua para consumo humano en Perú." [Online]. Available: http://www.agq.com.es/article-es/calidad-del-agua-para-consumo-humano-peru. [Accessed: 15-Jun-2018].

[23] O. US EPA, "Revised Total Coliform Rule And Total Coliform Rule," *US EPA*, 13-Oct-2015. [Online]. Available: https://www.epa.gov/dwreginfo/revised-total-coliform-rule-and-total-coliform-rule. [Accessed: 15-Jun-2018].

[24] L. Zhong and S. Youchao, "Research on Maintainability Evaluation Model Based on Fuzzy Theory," *Chin. J. Aeronaut.*, vol. 20, no. 5, pp. 402–407, Oct. 2007.