# Multi-Objective Optimization and Scenario-based Robustness Analysis of the MoneyMaker Hip Pump

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# Abstract

Water-lifting technologies for irrigation have significant potential to increase agricultural yields and stimulate economic growth in rural areas of the developing world. Human-powered water pumps have been used with great success in this rapidly developing market. KickStart's MoneyMaker Hip Pump is a human-powered water pump with additional design features that make it lightweight and portable for use in remote fields in several countries throughout Africa. This work first applied numerical optimization techniques to the design of the MoneyMaker Hip Pump and offers further improvements to its design. Deterministic multi-objective optimization methods were employed to maximize the flow rate of the pump, maximize the pumping height of water, and minimize cost. Following optimization, the robustness of the optimized pump design was analyzed under several modified scenarios, including fouling of the hoses and a decrease in operator power due to fatigue or aging. The set of cost-optimized pump designs was then compared to a second set of optimal designs that was found using material volume as a simplified proxy for the cost objective function. Findings indicate that several technical improvements can be made to the current MoneyMaker Hip Pump design to reduce cost by up to 37% without affecting water flow rate, or increase water flow rate by up to 88% without increasing cost. The numerical model was validated through physical experimentation of the MoneyMaker Hip Pump, and design alterations to reduce cost were experimentally shown to maintain pump performance.



*Keywords: design; irrigation; human-powered pump; multi-objective optimization; robustness.*

# 1 Introduction

Rural villages in developing countries face many hardships, including a lack of basic infrastructure, insufficient health care facilities, limited educational opportunities, little access to clean water and energy, long workdays completing household tasks, and sparse opportunities for entrepreneurship and economic growth [1–3]. Governmental and non-governmental organizations have provided significant financial and material aid over the last sixty years, but the extent of poverty in rural areas has remained largely unchanged [4]. In contrast to traditional humanitarian aid in which governments and large organizations act as intermediaries, market-based approaches seek to increase economic activity in developing countries via entrepreneurship. Market-based strategies can be more effective than traditional aid because they use a bottom-up approach to boost local business development and increase individual income [5].

Many development organizations target the agricultural sector of developing countries because subsistence agriculture or small-scale farming is the primary occupation in rural areas [6]. Reliable irrigation techniques have been shown to increase crop yields by at least 100% and at most 400% [7]. The resulting increase in crop yield translates to increased sales and income, and can allow farmers to cultivate higher-value crops and adopt new technologies. The rise in income allows farmers to expand arable land and further increase production and income each season. This incremental, yet significant, improvement is attainable without conventional pumping techniques that require substantial financial investment relative to income. For instance, diesel pumps are effective for irrigation but the capital cost and fuel costs prohibit use by many subsistence farmers [8].

Human-powered pumps are a popular option for farmers with small plots of land given the low capital cost and operating cost [9]. Perhaps the most ubiquitous of these is the foot-powered treadle pump, invented by the Norwegian engineer Gunnar Barnes in the 1970s [1] and first introduced in Bangladesh [10]. Since the inception of the treadle pump, companies such as International Development Enterprises (IDE) and KickStart have re-designed the treadle pump and introduced a variety of other human-powered pumps. Current treadle pump designs can draw water from depths reaching 7 m at flow rates up to 5 L/s [10,11]. Human-powered pumps have helped numerous subsistence farmers transition out of poverty [12–15].

The basic treadle design was modified by KickStart to meet consumer demands for portability and to permit hand operation instead of foot operation [16]. The resulting MoneyMaker Hip Pump (see Figure 1) has a suction lift of 7 m. The pump is also capable of delivering water with a head of up to 7 m, but the typical use case is usually closer to 3 m [17].

**(a) Computer model** [18]. **(b) During use** [19].

**Figure 1. The MoneyMaker Hip Pump.**

Human-powered pumps are an effective irrigation solution for many subsistence farmers but problems have been observed during deployment. For instance, from 1995 to 2005 treadle pumps were freely distributed to farmers in Malawi. However, 60% of the pumps were not put to use [20]. Evidence suggests that the scarcity of spare parts and lack of well-organized markets restricted adoption [14]. Studies have also indicated that adoption might be improved through modifying the socio-economic system in which pumps are distributed and operated [14,21].

Data suggests that treadle pump output is typically small and is independent of the body type of the operator [22]. These performance barriers of human-powered pumps are one factor limiting their adoption. It is also clear that adoption rates are closely related to ease-of-use. Work by Lewis et al. led to the creation of a modular treadle pump design that could be reconfigured with additional components to achieve progressively higher pump performances [23,24]. In that work, a series of pump designs began with a low-cost module that could be expanded with a higher-performing module once earnings increased as a result of using the basic pump design. Design trade-offs between cost and performance of the treadle pump have been explored through design optimization and engineering analysis but limited studies have been completed for hand-powered pumps [25].

This work developed a volumetric fluid model of the MoneyMaker Hip Pump and applied multi-objective optimization techniques to maximize flow rate, maximize delivery head, and minimize cost. The resulting set of optimized solutions (referred to as a Pareto set) sought to balance the competing objective functions. Optimal pump designs were further analyzed under several scenarios, including fouling of the hoses and decreased operator power through fatigue or aging, to assess the robustness of the optimal designs. Finally, experimental verification of the volumetric fluid model and partial validation of the optimization results was undertaken.

## 2 The Physical System

Design specifications for the MoneyMaker Hip Pump include drawing water from a well up to 7 m deep, transporting the water at ground level through a hose approximately 18 m in length, and pumping water up into a tank of 3 m in height [18]. Tank placement of 3 m above ground is the typical use case specified by Kickstart and is within the maximum rated water delivery head of 7 m.

Figure 2 shows the MoneyMaker Hip Pump with all physical dimension variables labeled. The inner and outer diameters of the pump inlet hose were denoted by $x_1$ and $x_2$, whereas $x_9$ and $x_{10}$ denoted the inner and outer diameters of the outlet hose. The inner and outer diameters of the pump cylinder were denoted by $x_3$ and $x_4$, respectively. Variables representing inner and outer diameter were constrained according to a regression analysis presented in this work. The length of the piston was denoted by $x_8$, and the length of the piston's stroke was denoted by $x_5$. The variables $x_6$, $x_7$, $x_{11}$ and $x_{12}$ described the position of the pump relative to the water source and the tank. These were closely related and heavily constrained according to a standard use configuration supplied by Kickstart [18]. The operation of the pump was further described by $x_{13}$ and $x_{14}$ (forces applied during the downstroke and the upstroke) and $x_{15}$ and $x_{16}$ (velocities of the downstroke and the upstroke). Variables $x_1$ through $x_{12}$ represented lengths and diameters, and were measured in meters (m); $x_{13}$ and $x_{14}$ were forces, measured in Newtons (N); and $x_{15}$ and $x_{16}$ were velocities, measured in meters per second (m/s).

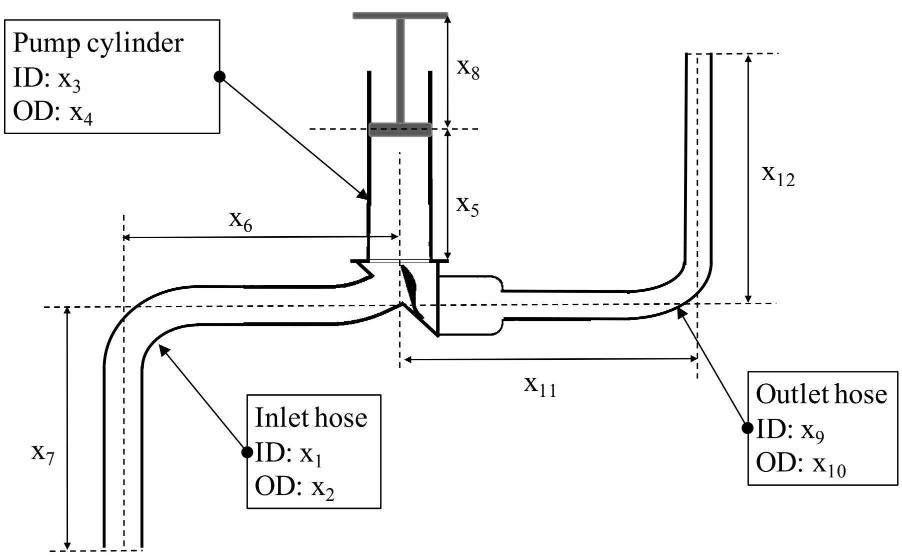


**Figure 2. Design dimensions, forces, and velocities of the MoneyMaker Hip Pump.**

**Table 1. Summary and descriptions of design variables.**

| Variable | Description | Units |
|---|---|---|
| $x_1$ | Inner diameter of the inlet hose | m |
| $x_2$ | Outer diameter of the inlet hose | m |
| $x_3$ | Inner diameter of the main pump cylinder | m |
| $x_4$ | Outer diameter of the main pump cylinder | m |
| $x_5$ | Length of stroke | m |
| $x_6$ | Horizontal distance from pump to well | m |
| $x_7$ | Depth of well | m |
| $x_8$ | Length of piston rod | m |
| $x_9$ | Inner diameter of outlet hose | m |
| $x_{10}$ | Outer diameter of outlet hose | m |
| $x_{11}$ | Horizontal distance from pump to tank | m |
| $x_{12}$ | Height of tank | m |
| $x_{13}$ | Force applied during downstroke | N |
| $x_{14}$ | Force applied during upstroke | N |
| $x_{15}$ | Velocity of downstroke | m/s |
| $x_{16}$ | Velocity of upstroke | m/s |

# 3 Numerical Optimization

This work employed numerical optimization techniques to identify technical improvements and cost reductions to the MoneyMaker Hip Pump. Specifically, multi-objective optimization was utilized to examine the effect of the design variables on the conflicting objective functions for flow rate, height of the tank, and projected pump cost. This yielded a set of cost-optimized solutions. This set of solutions was then compared to solutions produced using a simplified objective function that computed material volume as an approximation of cost. An economic approximation that uses volume as a proxy for cost might be used in early stages of design, before manufacturing methods and materials have been selected. The accuracy of such approximations is important because much of a product's final cost is committed during the early stages of design [26,27].

## 3.1 Methodology

This section introduces the objective functions, constraints, and algorithmic approach used in the optimization study.

### *3.1.1 Objective Functions*

The optimization study included three objective functions. The first objective function, water flow rate, was computed as

$$F_1(x) = \eta_V 0.25\pi \cdot x_3^2 x_5 \cdot \left(\frac{x_5}{x_{15}} + \frac{x_5}{x_{16}}\right)^{-1}. \quad (1)$$

In this equation, the terms $x_5/x_{15}$ and $x_5/x_{16}$ compute the length of time required for a downstroke and upstroke, respectively. A summation of these together gives the total time required for one cycle of the pump. During one cycle, the volume of water moved is equal to the volume of the cylinder, computed as $0.25\pi \cdot x_3^2 x_5$. Dividing the volume of the cylinder by the time for one cycle yields the average flow rate of water supplied by the pump. The variable $\eta_V$ denotes the volumetric efficiency of the pump. When referring to a hydraulic pump, volumetric efficiency is the ratio of actual fluid flow from the pump to theoretical fluid flow (without leakage). This value is estimated as 99% (on the order of 1 mL/s leakage), and is representative of low leakage that would be expected for a recently manufacturing pump with little wear. This value is subjected to robustness analysis in subsequent sections to ascertain the effects of increased leakage on overall pump performance.

The second objective function, tank height, was defined simply as

$$F_2(x) = x_{12}. \quad (2)$$

The third objective was formulated in two different ways. The first formulation, denoted by $F_3^C$, computed the projected cost of a pump using the known cost of components in the MoneyMaker Hip Pump. The second formulation, denoted by $F_3^V$, used material volume as a proxy for cost with a simplified equation set.

The cost objective, $F_3^C$, accounted for the bulk material cost of hoses and used scaling relationships to estimate the cost of other components:

$$F_3^C(x) = C_{h,in} + C_{h,out} + C_{cyl} + C_{pist} + C_{body} \quad (3)$$

$$C_{h,in} = \frac{\pi}{4} C_{HDPE}(x_6 + x_7)(x_2^2 - x_1^2) \quad (4)$$

$$C_{h,out} = \frac{\pi}{4} C_{HDPE} (x_{11} + x_{12}) (x_{10}^2 - x_9^2) \quad (5)$$

$$C_{cyl} = C_U \left( \frac{x_4}{x_{4,R}} \right) + C_{PC} \left( \frac{x_4 - x_3}{x_{4,R} - x_{3,R}} \right) \left( \frac{x_5}{x_{5,R}} \right) \quad (6)$$

$$C_{pist} = C_{SW} \left( \frac{x_3 - 0.006}{x_{3,R} - 0.006} \right)^2 + C_{LW} \left( \frac{x_3}{x_{3,R}} \right)^2 + C_{HR} \left( \frac{x_8}{x_{8,R}} \right) + C_{SC} \left( \frac{x_4}{x_{4,R}} \right) \quad (7)$$

$$C_{body} = C_{IPL} \left( \frac{x_1}{x_{1,R}} \right)^2 + C_{OPL} \left( \frac{x_9}{x_{9,R}} \right)^2 + C_{TPL} \left( \frac{x_3}{x_{3,R}} \right)^2 + C_N \left( \frac{x_3}{x_{3,R}} \right) + C_{OP} \left( \frac{x_9}{x_{9,R}} \right) + C_{IP} \left( \frac{x_1}{x_{1,R}} \right) \quad (8)$$

The function $F_3^C$ was defined as a linear combination of terms with each term describing the cost of a specific pump component. These terms include a reference cost for each component that is scaled with respect to the value of the design variables that impact the cost of the component (e.g., length of cylinder, diameter of cylinder). Cost and sizing constants associated with each term in $F_3^C$ are provided in Table 2. These components account for the largest and most expensive components in the MoneyMaker Hip Pump. Smaller components (e.g., gaskets or spacers) would not vary significantly in cost between different designs and were therefore omitted from the cost function in the interest of simplicity. The evaluation of design alternatives looks at comparisons between optimized designs rather than the absolute pump production cost.

**Table 2. Constant values for objective functions** [18]**.**

| Constant | Description | Value |
|---|---|---|
| $C_U$ | Cost of union between cylinder and valve box | 0.75 USD |
| $C_{PC}$ | Cost of pump cylinder | 1.96 USD |
| $C_{SW}$ | Cost of small washer | 0.31 USD |
| $C_{LW}$ | Cost of large washer | 0.45 USD |
| $C_{HR}$ | Cost of handle rod | 1.57 USD |
| $C_{SC}$ | Cost of splash cup | 0.74 USD |
| $C_{IPL}$ | Cost of inlet plate | 0.88 USD |
| $C_{OPL}$ | Cost of outlet plate | 1.09 USD |

| | | |
|---|---|---|
| $C_{TPL}$ | Cost of top plate | 1.09 USD |
| $C_N$ | Cost of nipple | 1.05 USD |
| $C_{OP}$ | Cost of outlet pipe | 1.13 USD |
| $C_{IP}$ | Cost of inlet pipe | 1.07 USD |
| $C_{HDPE}$ | Volumetric cost of HDPE | 3808 USD/m$^3$ |
| $x_{1,R}$ | Reference value of $x_1$ | 0.017 m |
| $x_{3,R}$ | Reference value of $x_3$ | 0.045 m |
| $x_{4,R}$ | Reference value of $x_4$ | 0.05 m |
| $x_{5,R}$ | Reference value of $x_5$ | 0.632 m |
| $x_{8,R}$ | Reference value of $x_8$ | 0.687 m |
| $x_{9,R}$ | Reference value of $x_9$ | 0.019 m |

This work also sought to simplify the cost objective function, $F_3^C$, with a volume-based objective function, $F_3^V$. The volume-based objective function assumed that (1) the cost of the pump was dictated primarily by material costs and (2) the pump was composed of material with a uniform cost. Although these assumptions are simplifying and may reduce accuracy, they would be required in the absence of detailed cost information necessary to evaluate $F_3^C$. Estimating costs of materials and manufacturing processes may add error if such estimates are inaccurate. By comparing results from the cost-based analysis and volume-based analysis, this work sought to assess the appropriateness of using volume as a proxy for cost during the optimization of human-powered pumps. The volume-based objective function was defined as:

$$F_3^V(x) = V_{h,in} + V_{h,out} + V_{cyl} + V_{pist} \tag{9}$$

$$V_{h,in} = \frac{\pi}{4}(x_6 + x_7)(x_2^2 - x_1^2) \tag{10}$$

$$V_{h,out} = \frac{\pi}{4}(x_{11} + x_{12})(x_{10}^2 - x_9^2) \tag{11}$$

$$V_{cyl} = \frac{\pi}{4}(x_4^2 - x_3^2)x_5 \tag{12}$$

$$V_{pist} = \frac{\pi}{4}D_{pist}^2 x_8 + \frac{\pi}{4}x_3^2 t_{cup} \tag{13}$$

### *3.1.2 Constraints*

Optimization was performed with respect to several constraints. Equality constraints are provided in Table 3 and inequality constraints are provided in Table 4. Equality constraints $h_4$ and $h_5$ were expressed using functions $H_L$ and $H_P$ to make those constraint equations more succinct. $H_L$ represents the major head loss in a pipe or hose and was defined as

$$H_L(L, V, D) = \frac{10.67L \cdot (0.25\pi D^2 V)^{1.85}}{C_{HW}^{1.85} D^{4.87}} , \quad (14)$$

where $L$ was the length of the hose or pipe, $D$ was its diameter, and $V$ was the velocity of the fluid. The function $H_P$ represents the head added by a pump, and was defined as

$$H_P(F, D) = \frac{F}{\rho g \cdot (0.25\pi D^2)} , \quad (15)$$

where $F$ was the force that the pump applies, and $D$ was the diameter of the pump cylinder. The degree of leakage past seals in the piston-cylinder assembly largely depends on the quality of the seals used, an aspect which was not addressed in the analysis. For that reason, water leakage was assumed to be negligible.

**Table 3. Equality constraints used in optimization model.**

| Equation | Description |
|---|---|
| $h_1(x)$: $x_2 - 1.094x_1 - 0.0028 = 0$ | Relationship between inner and outer diameter of inlet hose |
| $h_2(x)$: $x_4 - 1.094x_3 - 0.0028 = 0$ | Relationship between inner and outer diameter of pump cylinder |
| $h_3(x)$: $x_{10} - 1.094x_9 - 0.0028 = 0$ | Relationship between inner and outer diameter of outlet hose |
| $h_4(x)$: $H_L(x_6 + x_7, x_{16}, x_1) + H_L(0.5x_5, x_{16}, \eta_V x_3) + x_7 + 0.5x_5 + \frac{x_{16}^2}{2g} - H_P(x_{14}, x_3) = 0$ | Constraint to solve fluid equation during upstroke |
| $h_5(x)$: $H_L(x_{11} + x_{12}, x_{15}, x_9) + H_L(0.5x_5, x_{15}, \eta_V x_3) + x_7 - 0.5x_5 - \frac{x_{15}^2}{2g} - H_P(x_{13}, x_3) = 0$ | Constraint to solve fluid equation during downstroke |
| $h_6(x)$: $x_7 - d_{well} = 0$ | Depth of well |
| $h_7(x)$: $x_6 + x_{11} - d_{horiz} = 0$ | Constraint on horizontal distance from tank to well |

Equations for $h_1$, $h_2$, and $h_3$ provided relationships for the inner and outer diameters of the inlet hose, pump cylinder (similar in size and composition to a plastic pipe), and outlet hose. The relationship dictating these equations was developed by applying ordinary least-squares regression to a set of available pipe and hose diameters provided by Kickstart (see Figure 3). Plastic pipes and hoses were evaluated separately and it was found that the relationship between inner and outer diameters followed similar trends. Therefore, a single linear fit was created to describe this relationship (shown in Figure 3 as a thick line). Figure 3 also indicates sizes of the hose and cylinder currently available for the MoneyMaker Hip Pump.

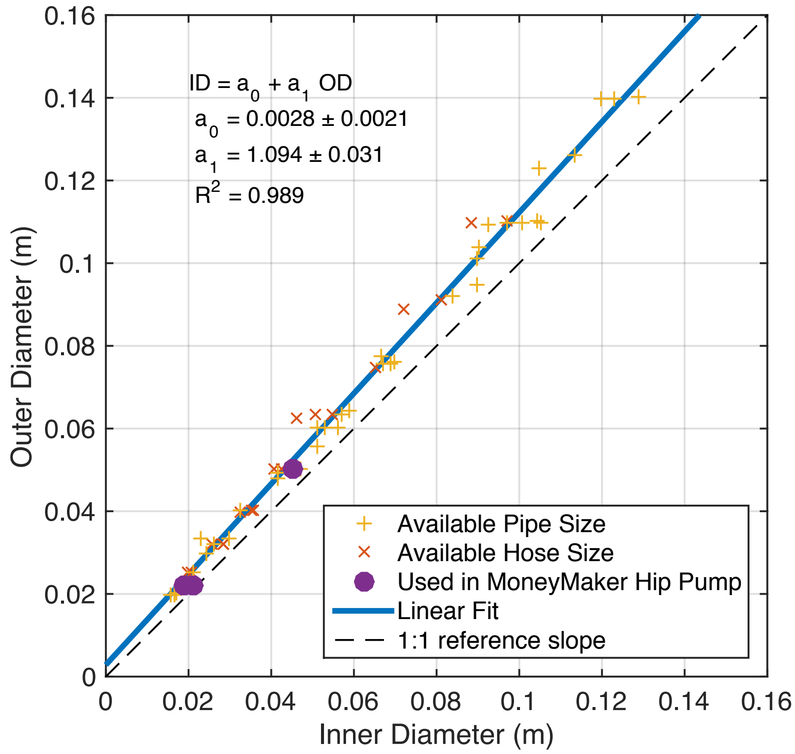


**Figure 3. Relationship between inner and outer diameter of hoses, used in equality constraints during optimization (error term for coefficients indicates 95% confidence interval).**

Inequality constraints were implemented to model a variety of physical phenomena and human factors (see Table 4). Constraints $g_1$ and $g_2$ restricted the power that could be applied by the pump operator during the downstroke and upstroke, respectively. The limiting power values of $P_{down}$ and $P_{up}$ were calculated from human experimental data derived a combination of male and female users (data provided by Kickstart) [18]. Using these average power values to constrain the optimization problem provided a means of implicitly relating the force and velocity to pump operation. This ensured that an average user would be able to operate any pump resulting from this work. This relationship does not account for user fatigue that may occur by quickly operating the pump with extremely fast strokes or extremely forceful strokes. A later section of this paper investigates the robustness of pump performance to decreased operator power in lieu of a data-driven time series model on user fatigue. Table 5 provides additional parameters and constants used in the inequality constraints listed in Table 3.

**Table 4. Inequality constraints used in optimization model.**

| Equation | Description |
|---|---|
| $g_1(x)$: $x_{13}x_{15} - \eta_M P_{down} \leq 0$ | Upper limit on average downstroke power |
| $g_2(x)$: $x_{14}x_{16} - \eta_M P_{up} \leq 0$ | Upper limit on average upstroke power |
| $g_3(x)$: $x_5 + x_8 - d_{shoulder} \leq 0$ | Upper limit on top extent of stroke |
| $g_4(x)$: $d_{knee} - x_8 < 0$ | Lower limit on bottom extent of stroke |
| $g_5(x)$: $t_{cycle} - \left(\frac{x_5}{x_{15}} - \frac{x_5}{x_{16}}\right) \leq 0$ | Minimum cycle time |
| $g_6(x)$: $x_5 - x_8 \leq 0$ | Piston must be longer than cylinder |
| $g_7(x)$: $\frac{x_{14}}{0.25\pi x_3^2} - p_{vp} \leq 0$ | Protects against cavitation during upstroke |

**Table 5. Parameters and constants.**

| Constant | Description | Value |
|---|---|---|
| $P_{down}$ | Average power supplied during downstroke | 27.7 W |
| $P_{up}$ | Average power supplied during upstroke | 33.7 W |
| $d_{shoulder}$ | Average height of shoulder | 1.3 m |
| $d_{knee}$ | Average height of knee | 0.5 m |
| $t_{cycle}$ | Lower limit on cycle time | 3 s |
| $g$ | Gravitational constant | 9.8 m/s$^2$ |
| $C_{HW}$ | Hazen-Williams coefficient for water | 140 |
| $\rho$ | Density of water | 1000 kg/m$^3$ |
| $d_{well}$ | Depth of well | 7 m |
| $d_{horiz}$ | Distance from well to tank | 18 m |
| $p_{vp}$ | Vapor pressure of water | 101.3 kPa |
| $\eta_M$ | Mechanical transfer efficiency | 90% |
| $\eta_V$ | Volumetric efficiency | 99% |

Values for $d_{well}$ and $d_{horiz}$ were set by Kickstart as the most common use case of the MoneyMaker Hip Pump [18] with values for $d_{shoulder}$ and $d_{knee}$ approximated based on the maximum stroke length during operation of the pump. The robustness of the optimal pump design choice was assessed against these approximations.

The mechanical transfer efficiency dictates how efficiently the power applied to the pump (by the operator) is transferred to the working fluid. In the MoneyMaker Hip Pump, mechanical transfer efficiency is reduced by frictional losses in the piston-cylinder assembly. These losses occur from sliding friction between the seal and the cylinder wall, and sliding friction between the piston shaft and the top cap of the cylinder. The latter may be exacerbated by imperfect alignment of the piston within the cylinder. A mechanical transfer efficiency of 80% has been used in other work that evaluated human-powered water pumps [24]. The pumps evaluated in that work utilized axles and levers in addition to water-lifting pistons. A higher mechanical transfer efficiency of 90% was assumed given that the MoneyMaker Hip Pump has a direct-driven piston.

The mechanical transfer efficiency ($\eta_M$) and volumetric efficiency ($\eta_V$) describe the efficiency of specific features of the pump – the overall system efficiency ($\eta_{SYS}$) of the pump includes these and other terms. The value of $\eta_{SYS}$ can be computed by comparing the total energy input to the pump during one full stroke to the total potential energy added to water during that stroke. This implicitly accounts for volumetric efficiency and mechanical transfer efficiency, as well as major and minor head losses that comprise the majority of system efficiency reductions. Because the head losses in hand-powered water pumps are usually substantial, the overall system efficiency is typically on the order of 10-20%. System efficiency can be increased through larger hoses, smoother materials, and shorter runs.

### *3.1.3 Optimization Algorithm*

Results of a multi-objective optimization problem are described as a Pareto set. The $\epsilon$-constraint method was used to resolve the Pareto set in this work [28]. This technique was instituted by specifying target values for $F_1$ and $F_2$ through two additional equality constraints

$$\begin{aligned} h_8(x)&:\ F_1(x) - Q_T = 0 \\ h_9(x)&:\ F_2(x) - H_T = 0, \end{aligned} \tag{16}$$

where $Q_T$ and $H_T$ are target values from the flow rate and tank height, respectively. The introduction of these equality constraints reframed the original multi-objective optimization problem as a single-objective optimization problem which could be solved by minimizing either $F_3^C$ (for cost-optimized pump designs) or $F_3^V$ (for volume optimal pump designs). Optimal solutions in the Pareto set were found through systematically varying the value of these targets to create a set of single-objective optimization problems.

The solution to each of these single-objective problems was found with the sequential quadratic programming algorithm from the MATLAB optimization toolbox. This algorithm solves the quadratic programming subproblem with routines proposed by Spellucci [29] and Tone [30], and completes a merit-function line search to determine the step size in design variables [31]. The algorithm was terminated when first order optimality was satisfied to within $10^{-6}$ and the maximum constraint violation was $10^{-6}$. This process was repeated 100 times for each optimization problem using initial conditions chosen uniformly at random within the design space. This randomized multi-start methodology increased the opportunity to identify the global optimum because a single starting point may converge on a local minimum.

## 3.2 Results and Discussion

The optimization problem was solved to produce two sets of optimal solutions: optimal solutions using the cost objective function ($F_3^C$), and optimal solutions using the volume objective function ($F_3^V$). The cost-optimized results were then subjected to a scenario-based robustness analysis performed to explore solution efficacy against uncertainties in environmental or anthropogenic factors. Finally, these volume-optimized results were compared to the cost-optimized results.

### *3.2.1 Cost-Optimized Results*

Multiple combinations of tank height and flow rate were evaluated during the exploration of the solution space. The target flow rate ($Q_T$) was varied from 0.02 L/s to 0.40 L/s in increments of 0.02 L/s. The target tank height ($H_T$) was varied from 0 m to 3 m in increments of 1 m. The multi-start optimization procedure described in Section 3 was completed for each combination of values. Figure 4 illustrates the Pareto set from this procedure. The cost and performance of the existing MoneyMaker Hip Pump design was simulated using the equations presented in this paper for tank heights of 0 m and 3 m and is displayed on Figure 4 with two diamonds. Simulated results of the existing MoneyMaker Hip Pump are situated to the upper-left of the cost-optimized pump designs in Figure 4 (behind the Pareto set), suggesting that Kickstart could improve upon its current design. Specifically, the cost of the pump can be kept constant while increasing the flow rate by more than 30% (for a 3m tank design) or by more than 80% (for a no-tank design). The cost of the pump could similarly be decreased while maintaining performance characteristics (both tank height and flow rate).

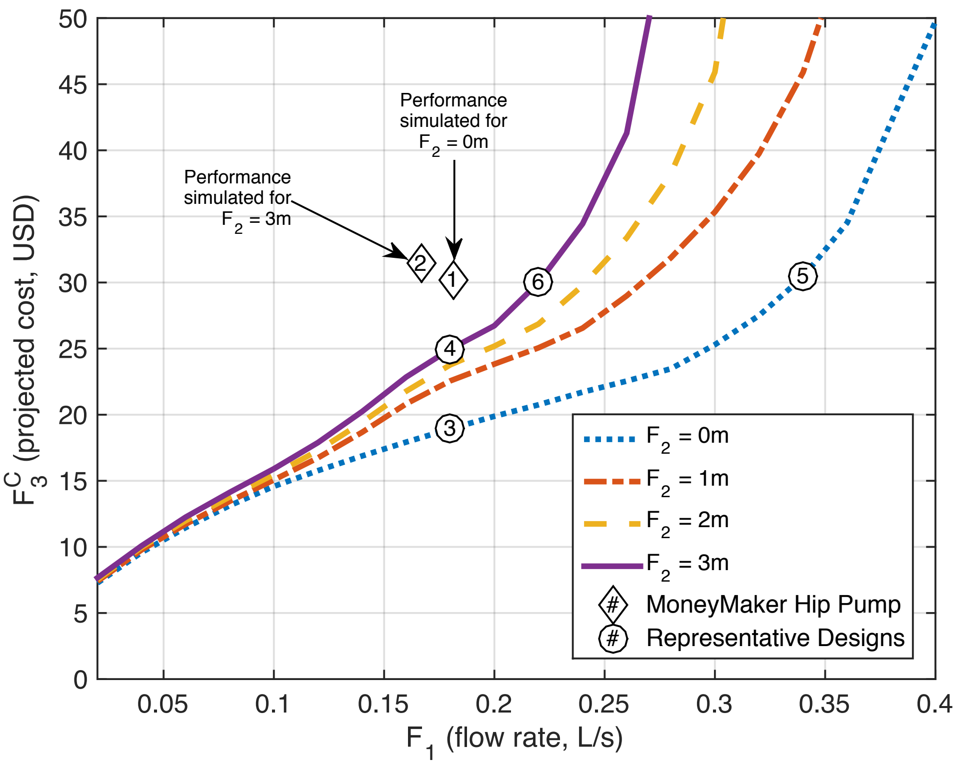


**Figure 4. Pareto set resulting from optimization study using cost objective function.**

The optimal pump designs shown with circle markers in Figure 4 are further detailed in Table 6 and in Figure 5. These pump designs were selected for comparison because they offer specific design improvements to the current MoneyMaker Hip Pump. Specifically, representative designs ③ and ④ maintain the flow rate of the current MoneyMaker design while minimizing cost (for both no tank and tall tank cases), whereas representative designs ⑤ and ⑥ maintain the same cost as the current MoneyMaker while maximizing flow rate (for both no tank and tall tank cases). Dimensions of the

MoneyMaker Hip Pump are also given in Table 6. Further, all designs from Table 6 are shown graphically in Figure 5.

**Table 6. Dimensions of MoneyMaker and representative designs along the Pareto set.**

| | 1<br>**MoneyMaker No Tank** | 2<br>**MoneyMaker Tall Tank** | 3<br>**Same Flow Min Cost No Tank** | 4<br>**Same Flow Min Cost Tall Tank** | 5<br>**Max Flow Same Cost No Tank** | 6<br>**Max Flow Same Cost Tall Tank** |
|---|---|---|---|---|---|---|
| $F_1$ | 0.181 L/s | 0.167 L/s | 0.180 L/s | 0.180 L/s | 0.340 L/s | 0.220 L/s |
| $F_2$ | 0.00 m | 3.00 m | 0.00 m | 3.00 m | 0.00 m | 3.00 m |
| $F_3$ | 30.17 USD | 31.48 USD | 18.93 USD | 24.96 USD | 30.43 USD | 29.99 USD |
| $x_1$ | 0.0210 m | 0.0210 m | 0.0146 m | 0.0170 m | 0.0225 m | 0.0188 m |
| $x_2$ | 0.0220 m | 0.0220 m | 0.0188 m | 0.0215 m | 0.0274 m | 0.0234 m |
| $x_3$ | 0.0450 m | 0.0450 m | 0.0404 m | 0.0404 m | 0.0478 m | 0.0410 m |
| $x_4$ | 0.0500 m | 0.0500 m | 0.0471 m | 0.0470 m | 0.0550 m | 0.0477 m |
| $x_5$ | 0.6320 m | 0.6320 m | 0.5000 m | 0.5015 m | 0.6516 m | 0.5792 m |
| $x_6$ | 3.0000 m | 3.0000 m | 18.0000 m | 18.0000 m | 18.0000 m | 18.0000 m |
| $x_7$ | 7.0000 m | 7.0000 m | 7.0000 m | 7.0000 m | 7.0000 m | 7.0000 m |
| $x_8$ | 0.6870 m | 0.6870 m | 0.5000 m | 0.5015 m | 0.6516 m | 0.5792 m |
| $x_9$ | 0.0190 m | 0.0190 m | N/A m | 0.0148 m | N/A m | 0.0213 m |
| $x_{10}$ | 0.0220 m | 0.0220 m | N/A m | 0.0191 m | N/A m | 0.0261 m |
| $x_{11}$ | 15.0000 m | 15.0000 m | 0.0000 m | 0.0000 m | 0.0000 m | 0.0000 m |
| $x_{12}$ | 0.0000 m | 3.0000 m | 0.0000 m | 3.0000 m | 0.0000 m | 3.0000 m |
| $x_{13}$ | 117.2 N | 136.2 N | 6.2 N | 62.5 N | 6.2 N | 45.0 N |
| $x_{14}$ | 123.7 N | 123.7 N | 130.0 N | 129.6 N | 150.0 N | 125.5 N |
| $x_{15}$ | 0.2128 m/s | 0.1831 m/s | 4.0000 m/s | 0.3986 m/s | 4.0000 m/s | 0.5538 m/s |
| $x_{16}$ | 0.2449 m/s | 0.2449 m/s | 0.1469 m/s | 0.2210 m/s | 0.2019 m/s | 0.2413 m/s |

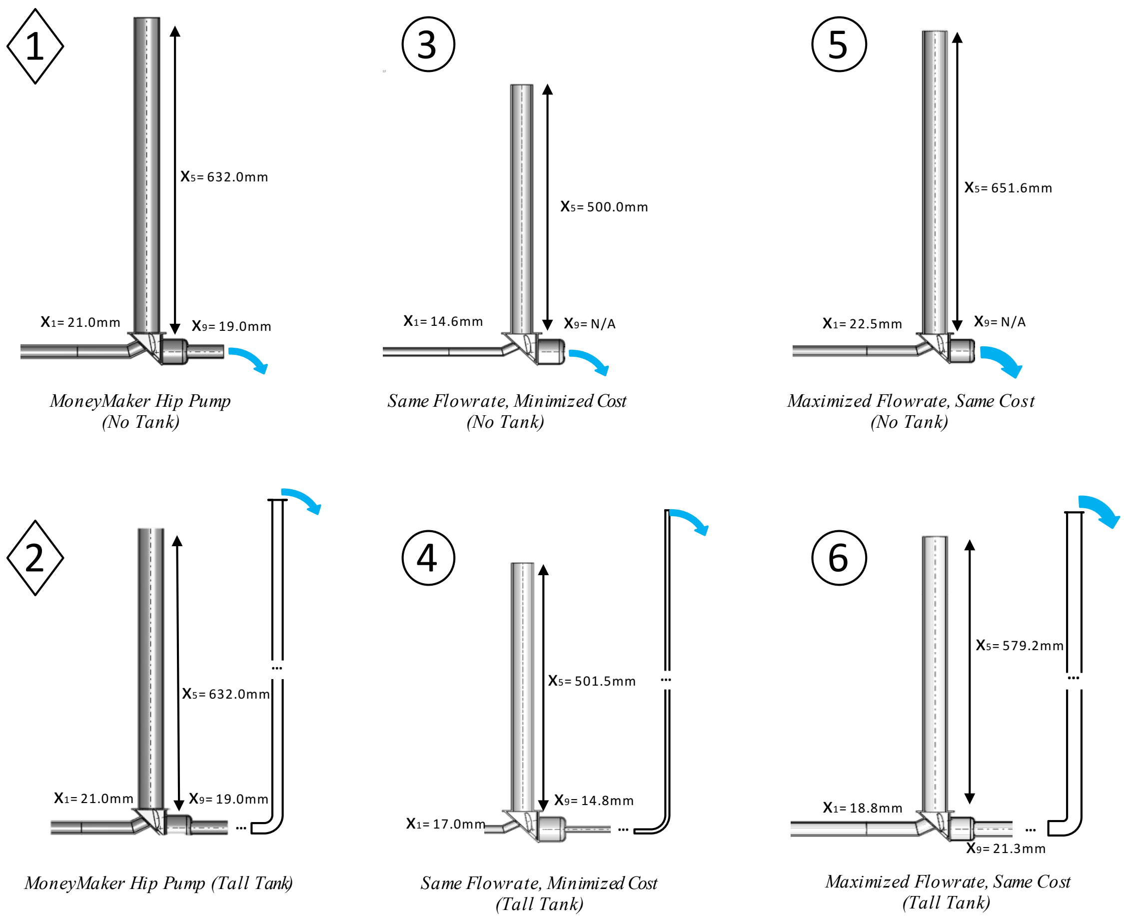


**Figure 5. Schematics showing differences between MoneyMaker and representative designs.**

These representative designs from the Pareto set of optimized pumps indicate that several improvements can be made to the MoneyMaker Hip Pump. Designs that maintain a similar flow rate to the current product while minimizing cost (i.e. representative designs ③ and ④ in Figure 5) show that the MoneyMaker is somewhat over-designed. A significant amount of material can be removed by shortening the piston, decreasing the diameter of hoses, and minimizing the length of the outlet hose. These changes could decrease the cost of the pump by anywhere from 21% (for the tall tank case) to 37% (for the no tank case) without sacrificing performance.

Designs that maintain a similar cost to the current product while maximizing flow rate (i.e. representative designs ⑤ and ⑥ in Figure 5) show that small design modifications can improve the product's functionality. For representative design ⑤, optimized for use without a tank, the flow rate can be increased by 88% by increasing the inner diameter of the inlet hose, eliminating the outlet hose, and increasing the diameter of the piston/cylinder assembly. The flow rate of representative design ⑥, optimized for a tall tank, can be increased by 32% by locating the pump immediately next to the tank, increasing the inner diameter of the outlet hose, decreasing the inner diameter of the inlet hose, and decreasing the length of the piston/cylinder assembly. These simple changes maintain the current pump cost while greatly increasing flow rate.

The above representative designs highlight the importance of pump location relative to the well and tank. Kickstart's standard use case indicates that the pump should be located approximately 3 m away from the top of the well (horizontally). However, the optimization process located the pump either directly over the well (for low flow rate designs) or at the tank (as demonstrated by the example designs in Figure 5). The placement of optimized pump designs is shown in Figure 6 as a function of the flow rate. For pumps that were optimized for zero tank height (indicated by the solid line), the pump location switched from the well to the tank at a flow rate of approximately 0.09 L/s. For all non-zero tank heights (indicated by the dashed line), the location switched at approximately 0.17 L/s.

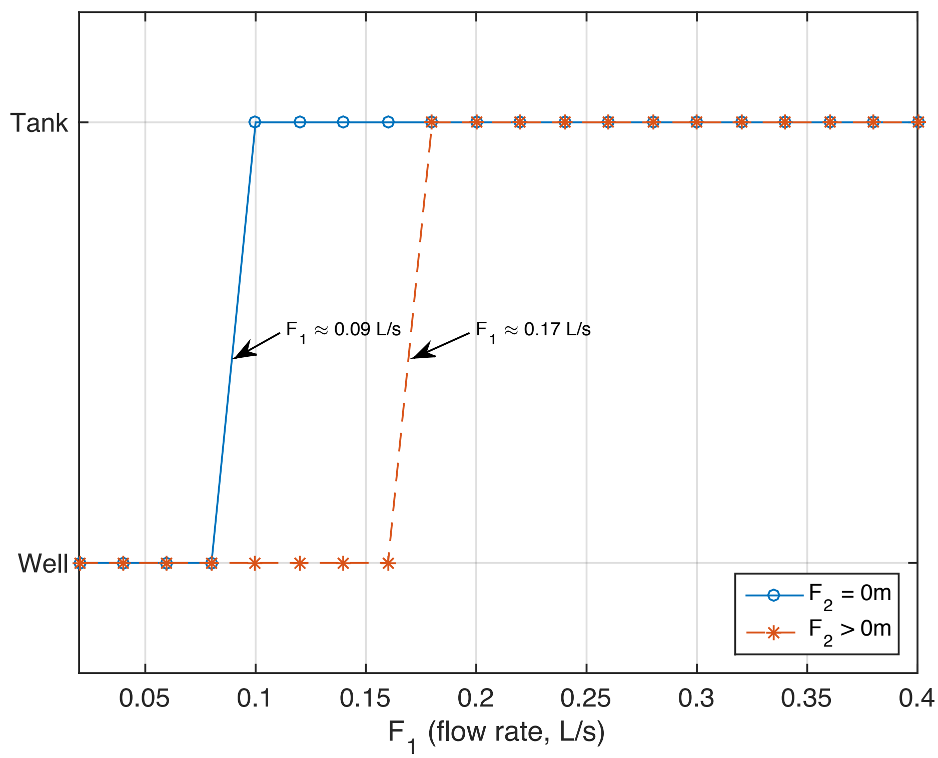


**Figure 6. Location of optimized pump designs.**

The similarity between optimal solutions was also of interest – whether design variables took on similar values (allowing the parts of the same size to be used on multiple pumps) or if designs were drastically different. This was examined by computing the aggregate difference between the values of solution variables. Specifically, we defined a partial solution vector

$$\tilde{x} = [x_1, x_2, x_3, x_4, x_5, x_8, x_9, x_{10}] \qquad (17)$$

which contained all variables except those that described the length of hoses ($x_6$, $x_7$, $x_{11}$, and $x_{12}$), and the operation of the pump ($x_{13}$ through $x_{16}$). The omission of those variables shifted the emphasis to the manufactured body of the pump, which contributes the majority of the cost in the MoneyMaker Hip Pump and is difficult to modify once produced. The difference between two optimal designs was then quantified using the $L^2$-norm of the subtractive difference between partial solution vectors:

$$d_{ij} = \left\| \tilde{x}_i - \tilde{x}_j \right\|_2. \quad (18)$$

In the above equation, $\tilde{x}_i$ and $\tilde{x}_j$ are the partial solution vectors corresponding to two optimal designs. This metric was used to perform a comparison of the cost-optimized solutions obtained for each value of optimal flow rate (see Figure 7). Specifically, every curve in the plot is a comparison between pumps that were optimized for two different tank heights. The x-axis indicates the flow rate that the pumps were originally optimized against, and the y-axis shows the value of $d$ (computed using Equation 16). A high value of $d$ means that two pump designs are dissimilar.

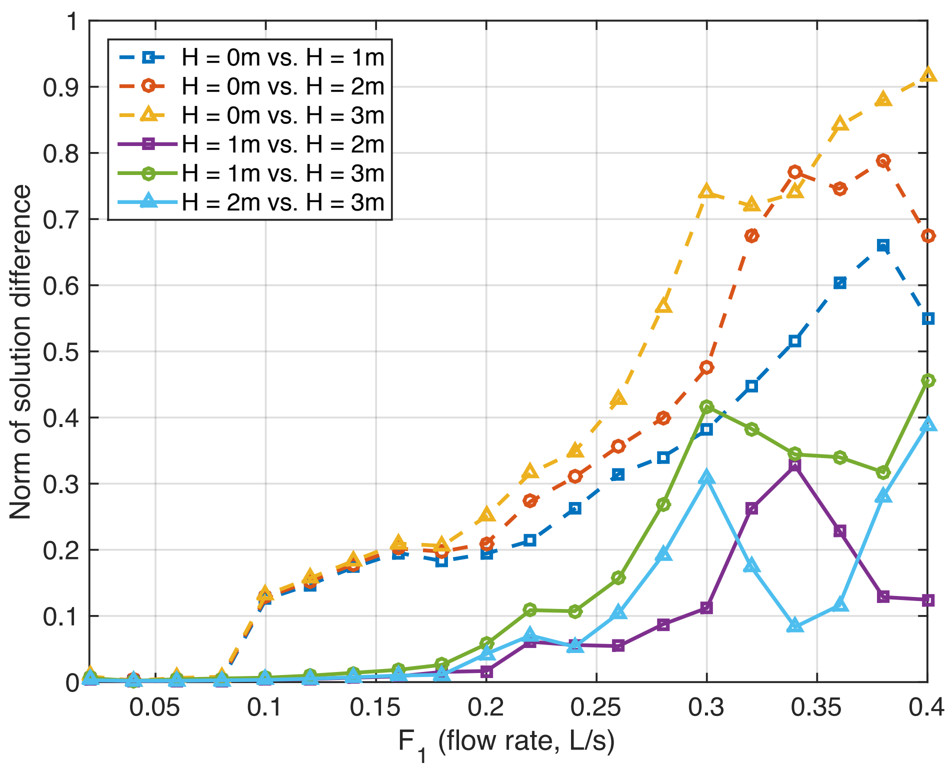


**Figure 7. Comparison of partial solution vectors for different optimal flow rates.**

All differences were approximately zero for optimal flow rates below 0.08 L/s. This indicates that the optimal solution values for low flow rates were independent of optimal tank height. For optimal flow rates greater than 0.08 L/s, the designs for non-zero tank height continued to be similar to one another (solid lines in Figure 7), while the zero tank height solutions began to differ from them (dash lines in Figure 7). For flow rates greater 0.18 L/s, all comparisons showed significantly non-zero differences.

Figure 7 indicates that the dimensions of optimal designs are independent of tank height for some conditions. Specifically, pump designs optimized for low flow rates (below 0.08 L/s) were optimal for any tank height from 0 m to 3 m. Pump designs optimized for moderate flow rates (from 0.09 L/s to 0.18 L/s) were simultaneously optimal for tank heights from 1 m to 3 m, but not 0 m. In other words, pumps that are optimized for low flow rates can be highly effective across a range of tank heights. The same is true to a lesser extent for pumps optimized for moderate flow rates.

These findings are noteworthy because they have implications for the development of a product platform with modular components to meet different user needs. A single pump design can be used at low flow rates (below 0.08 L/s) across multiple tank heights, indicating that multiple product lines (a product family) are not necessary for target markets in that flow rate range. At medium flow rates (between 0.08 L/s and 0.18 L/s) a different develops between pumps designed for zero tank height and any pump with a non-zero tank height – this points to the development of two product lines for medium flow rates. At high flow rates (above 0.18 L/s) a higher number of product lines may be necessary, as significant differences appear between pumps optimized for different tank heights.

#### *3.2.2 Robustness Analysis of Cost-Optimized Results*

The previous section provided optimized pump designs for specific operating conditions. However, products are commonly deployed and then used under a variety of operating conditions. This challenge was confronted by examining several scenarios with different operating conditions under which the pumps were not optimized. These four modified scenarios were:

1. decrease in the interior diameters of the hoses — caused by either organic or inorganic fouling;
2. decrease in the stroke length — pump is operated by someone of small stature;
3. decrease in power transferred to water — operator is fatigued/weak or mechanical transfer efficiency of pump decreases;
4. increase in well depth — water depth varies by location or season; and

5. decrease in volumetric efficiency — aging and wear of the pump components causing increased leakage.

Each scenario was explored through 5%, 10%, and 20% changes in the relevant values. Pump design robustness under these scenarios was assessed in two steps. First, the target parameter in each scenario was varied by the appropriate percentage. Next, the flow rate of the pump was maximized with respect to the operator input ($x_{13}$, $x_{14}$, $x_{15}$, and $x_{16}$), All other parameters were held constant and relevant constraints from Tables 2 and 3 were accounted for during this process. This procedure was repeated for all optimal pump designs discovered through the multi-objective optimization. The decrease in flow rate was computed for each solution, and the results are shown in Figure 8. The horizontal axis refers to the optimal flow rate from the initial optimization of the pump, while the contours indicate the decrease in actual flow rate caused by the modified scenario. The vertical axis indicates the tank height for which the pumps were optimized.

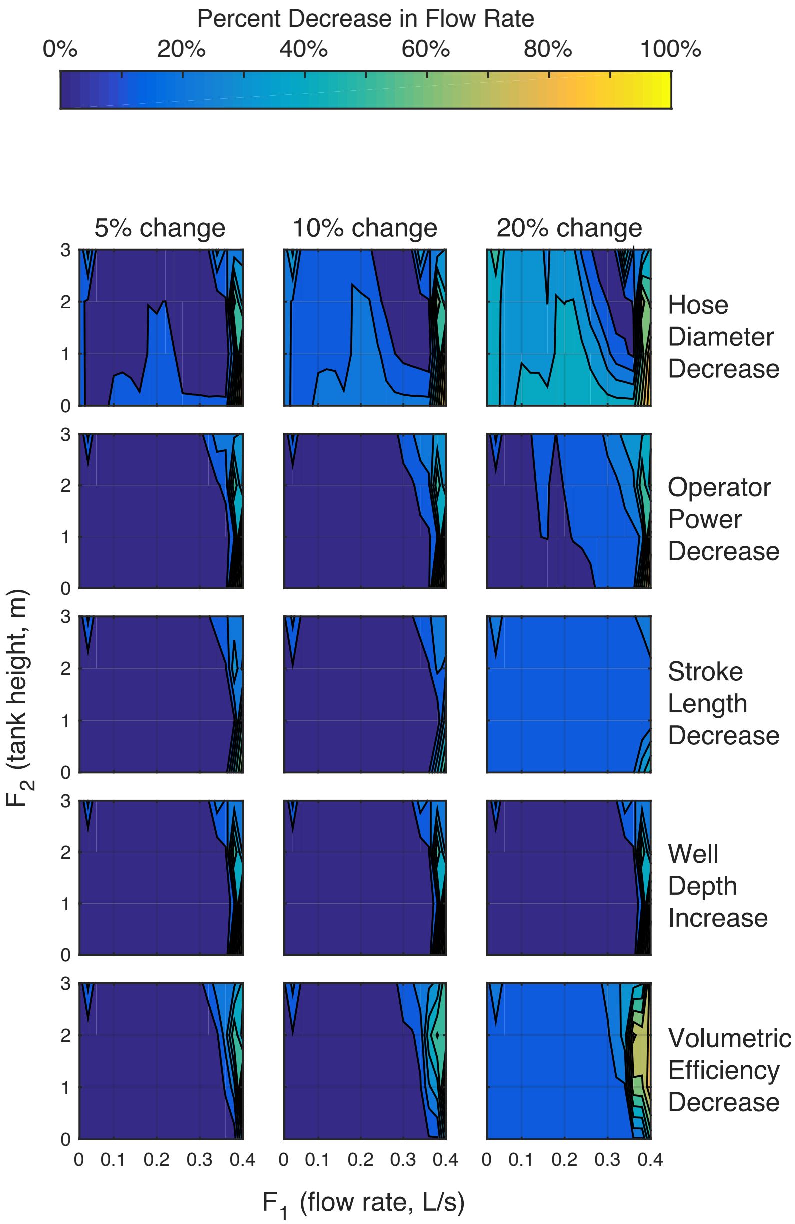


**Figure 8. Percent decrease in flow rate for modified scenarios.**

Decreases in hose inner diameter yielded the greatest decrease in pump performance (see Figure 8, first row). Surfaces in those contour plots are highly multi-modal. This reflects the tightly coupled nature of constraints associated with minor head losses in the hoses, the energy balance, and the operator input power to the pump.

The impact of decreases in the operator's power output was low for pumps optimized for low flow rates and low tank heights (see Figure 8, second row). For higher optimal flow rates and tank heights, however, lower operator power resulted in larger decreases in water flow rate. This scenario is closely tied to modeling assumptions for mechanical transfer efficiency. Decreased operator power could occur as a result of operator fatigue or increased friction (decreased mechanical transfer efficiency) in the pump.

Decreases in the operator's stroke length appear to have a consistently positive correlation with decreases in flow rate for most pumps that were optimized for flow rates below 0.3 L/s (see Figure 8, third row). This trend was expected when noting that the length of the piston stroke (assumed to be 100% during optimization) directly affects how much water the pump could draw in one cycle. Decreasing the available cylinder volume in this way necessarily decreases the flow rate of the pump. Increases to well depth (see Figure 8, fourth row) had the least impact with a decrease in flow rate of less than 1% for all cases below flow rates of 0.3 L/s, indicating that optimal pumps could provide a constant water flow rate for deeper wells if the operator selects an appropriate speed and force for operating the pump.

The final row in Figure 8 shows the result of drastically decreasing the volumetric efficiency of the pump (i.e. greatly increasing pump leakage). This could occur as pump seals wear down and become less effective. For most optimal pump designs, the relationship between the change in volumetric efficiency and the change in performance was linear, much like the effect of decreased stroke length on performance. However, pumps that were optimized for high flow rates (above 0.3 L/s) experienced large decreases in flow rate. This indicates that the quality and expected life of seals in the pump should be an important concern when manufacturing this pump.

Pumps that were optimized for lower flow rates (below approximately 0.1 L/s) displayed high robustness, particularly with respect to changes in operator power output. A similar trend has been identified for IDE-style treadle pumps in other work [32]. This may indicate that high robustness to operator input for low flow rates may be a general characteristic of human-powered pumps.

### *3.2.3 Comparison to Volume-Optimized Results*

The multi-objective optimization problem was again solved after replacing the cost objective function ($F_3^C$) with a simplified volume-based objective function ($F_3^V$). The projected cost of the volume-optimized solutions was then computed using Equations 3-8, thus allowing direct comparison between the results of each optimization study. The purpose behind this comparison was to assess the accuracy of using volume-based objective function as a proxy for projected cost. This is an insightful comparison because decisions made in early stages of the design process have a large impact on a product's final cost, at a point when detailed cost models may not be available [26,27].

Pump cost increased for all solutions found using the volume-based objective function (compared to solutions found using the cost-based objective function). This was because the cost-based optimization study specifically searched for and found solutions with lowest projected cost. Therefore, any other solution found using the volume-based objective function would have equal or higher projected cost. Figure 9 shows the percent increase in cost as a function of optimal tank height and optimal flow rate. The increase in cost was well below 10% for most operating conditions. However, for pumps that were designed for high flow rates increase in projected cost increased by up to 80%.

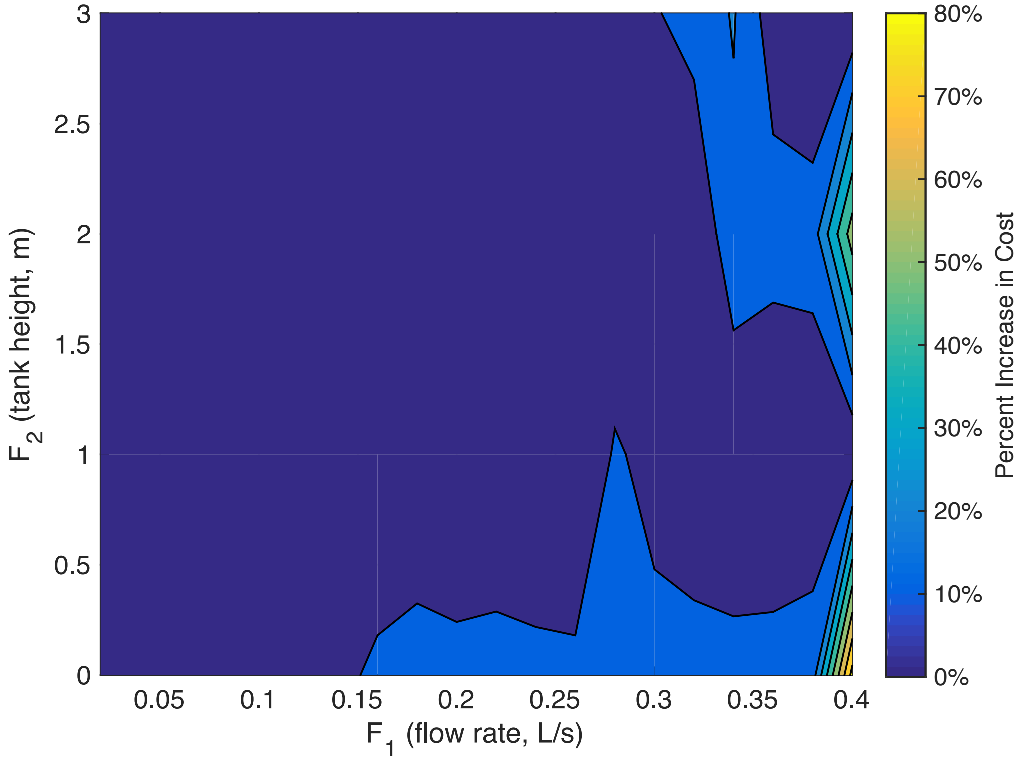


**Figure 9. Comparison of projected costs between cost-optimized and volume-optimized solutions.**

Examining differences between design variable values resulting from volume- and cost-based objective functions offered another form of comparison. The $L^2$-norm of the difference between partial solution vectors was used to compare parameters between cost-optimized designs and volume-optimized designs. This comparison is shown in Figure 10 as a function of optimal flow rate and optimal tank height. Higher values indicate that the solutions are different, while lower values indicate that the solutions are similar.

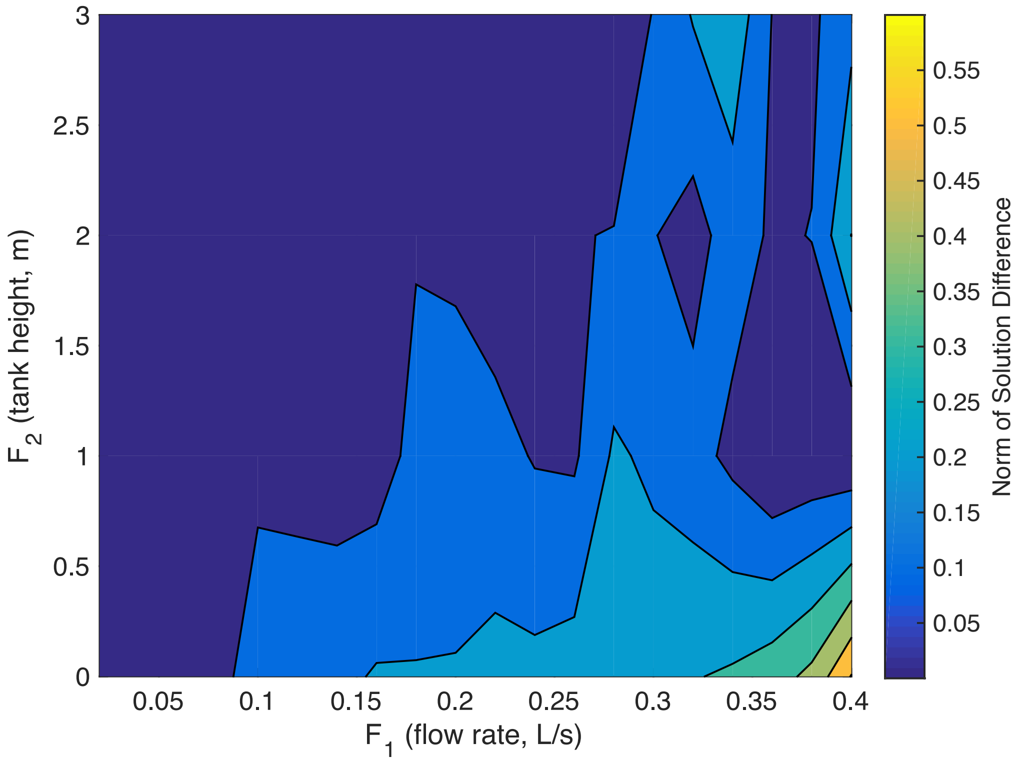


**Figure 10. Comparison of solution parameters between cost-optimized and volume-optimized solutions.**

Figure 10 indicates that a simplified volume-based objective function was capable of providing solutions that were similar in projected cost. The large region of Figure 10 that corresponds to a cost increase of less than 10% illustrates that this was true across a large range of both lift height and flow rate. However, Figure 11 shows that the agreement between solution variables using the two optimization approaches was not universal. Significant departures in both solution parameters and projected cost were found at (i) high flow rates and low tank heights, and (ii) high flow rates and high tank heights. For moderate flow rates and non-zero tank heights, there was close agreement for the projected cost but non-negligible differences were present in design parameters.

Based on this analysis, it is possible to conclude that the validity of using a volume-based approximation for the cost of a product is highly dependent on the design requirements of that product. Volume can be used to approximate cost for design problems involving a low flow rate but this method of approximation generally weakens at high flow rates.

Further work is necessary to determine whether this relationship can be generalized for other human-powered water pumps.

# 4 Experimental Verification and Validation

Following the completion of the numerical optimization study, an experiment was designed to rapidly verify the quality of assumptions made in modeling the MoneyMaker Hip Pump as well as to validate the efficacy of a design changes suggested in the numerical portion of this work.

## 4.1 Methodology

The first objective of this experiment was to validate assumptions made in modeling the physical system. This can be accomplished by assessing the overall system efficiency of the pump system, given as:

$$\eta_{SYS} = \frac{\rho g V_{cycle}(x_7 + x_3)}{(x_{13} + x_{14})x_5}, \quad (19)$$

where $V_{cycle}$ is the volume of water lifted by the pump during one cycle. The numerator of the equation computes the potential energy added to this volume of water. The denominator computes the work done on the pump by the operator during one single pump cycle (one upstroke and one downstroke). Comparing the values of $\eta_{SYS}$ computed from numerical simulations to those computed from experimental data would make it possible to assess the overall quality of the numerical model.

The second objective of this experiment was to validate the efficacy of potential design changes recommended by the optimization results. The numerical optimization showed that small design changes (i.e. representative designs ③ and ④ in Figure 5) could significantly decrease the cost of the MoneyMaker Hip Pump without sacrificing performance. The primary difference between these optimized designs and the current product is a decrease in the cylinder/piston length to approximately 0.5 m. An experimental comparison of the current product to a modified version with a shorter cylinder/piston assembly would provide validation of this design recommendation.

Fulfilling the two objectives above required the experimental measurement of two quantities: force applied to the pump by the operator and volume of water pumped. A MoneyMaker Hip Pump was instrumented to measure these quantities and an experimental environment was constructed to adhere closely to the typical use case specified by Kickstart (with the exception that a 4 m deep well was used due to facility limitations). Three experimental conditions were assessed:

1. MoneyMaker Hip Pump in standard configuration with no tank.
2. MoneyMaker Hip Pump in standard configuration with 3 m tank.
3. Modified MoneyMaker Hip Pump in standard configuration with 3 m tank. For this condition, the effective cylinder length was reduced to 0.5015 m.

For each of these experimental conditions, five one-minute pumping episodes were conducted to afford rapid evaluation and comparison. Conditions 1 and 2 provided baseline operational characteristics for the pump, making it possible to compute experimental efficiency values and fulfill the first experimental objective. Comparing the flow rates achieved in Conditions 2 and 3 made it possible to assess the second experimental objective.

## 4.2 Results and Discussion

Experimental results for overall efficiency and flow rate are summarized in Table 7. Mean values are provided with estimates of standard deviation.

**Table 7. Summary of experimental results.**

| | **Condition 1** *Moneymaker with no tank* | **Condition 2** *Moneymaker with tall tank* | **Condition 3** *Modified Moneymaker with tall tank* |
|---|---|---|---|
| Average efficiency (%) | 11.1 ± 1.3 | 15.2 ± 3.0 | 16.5 ± 0.7 |
| Average flow rate (L/s) | 0.073 ± 0.002 | 0.070 ± 0.004 | 0.069 ± 0.003 |

Assessing the first experimental objective requires a comparison of the experimental system efficiency of Conditions 1 and 2 with the corresponding efficiencies computed for equivalent simulated systems. The simulated efficiency (using the experimental model from Section 3) is 10.0% for Condition 1, and 15.9% for Condition 2. This aligns closely with the average experimental efficiencies (11.1% and 15.2%, respectively) indicating that the system-level characteristics of the numerical model are veridical. This generally lends credence to the numerical results shared in this work.

Evaluating the second experimental objective simply requires a comparison of the average flow rates achieved for Conditions 2 and 3. Condition 2 tested the unmodified MoneyMaker Hip Pump whereas Condition 3 tested a pump that was optimized to offer the same performance at a lower cost. The optimization study predicted that lower cost could be achieved without sacrificing performance primarily by shortening the pump cylinder/piston assembly (see representative designs ③ and ④ in Figure 5). The experiment flow rates for these conditions (see Table 7) are not statistically different, indicating that this design modification achieves the desired goals. Manufacturing pumps with these recommended dimensions could decrease cost by up to 21% and make the pump lighter and more portable, all while maintaining performance.

In sum, these experimental results support the numerical findings offered in Section 3 of this paper. The overall efficiency of the numerical model is very close to the overall efficiency of the physical system, indicating a sound modeling approach. Further, one of the design recommendations made in the optimization study was directly validated.

# 5 Conclusion

This work applied detailed engineering analysis and experimentation to a ubiquitous piece of technology that has been deployed in developing countries, and uncovered several improved design alternatives. Specifically, this work used deterministic multi-objective optimization techniques to optimize the physical construction of the MoneyMaker Hip Pump, a lightweight hand-operated water pump. First, the Pareto set for cost-optimized pumps was developed and examined. Second, the robustness of each cost-optimized pump was examined for a variety of modified scenarios. Third, the optimization was repeated using a volume-based formulation as a simplified proxy for the cost-based formulation. These numerical results were compared, discussed, and then experimentally validated. The results from this work indicated that multi-objective optimization could be a viable means of maximizing the performance of the MoneyMaker Hip Pump while maintaining a constant cost, or minimizing cost while maintain constant performance. Some of the major findings that resulted from this work were:

- Optimized pumps from this work offer alternative designs to improve the current MoneyMaker Hip Pump design on cost and performance merits, with a 37% reduction in cost for a fixed flow rate or an 88% increase in flow rate for a fixed cost.
- The current MoneyMaker Hip Pump can be redesigned to decrease cost while maintaining performance by decreasing hose diameters and decreasing the diameter and length of the main cylinder. The current design can also be modified to deliver higher flow rates at the same cost by increasing the diameter of the inlet hose and increasing the diameter of the cylinder assembly. See Table 6 for specific design recommendations.
- Optimized pumps were located either directly over the well for low flow rates (below 0.09 L/s for zero tank height, or below 0.17 L/s for non-zero tank height), or at the tank for higher flow rates, but never in between the tank and the well. This finding could provide a rule of thumb for future design and operation.
- Pumps that were optimized for low flow rates (less than 0.08 L/s) were highly effective across a range of tank heights. This was also true to a lesser extent for pumps that were optimized for moderate flow rates (0.08 – 0.18 L/s). For higher flow rates (greater than 0.18 L/s) the dimensions of optimal solutions were highly dependent upon tank height. This information could be used to efficiently produce a product family of pumps.
- Increases in the depth of the well had little impact on the performance of the optimized pump designs. This indicates that an optimized pump can maintain performance across water table depths that vary by location or season.

- Decreases in hose diameter due to fouling had a substantial impact on the performance of the pumps. Hose material should be selected with this consideration in mind. Increases in leakage could also affect pump performance. Therefore, seals should be selected for longevity and details of the pump designed for easy seal replacement.

- Decreases in stroke length had a one-to-one correspondence to pump flow rate (e.g. a 10% decrease in stroke length results in a 10% decrease in flow rate). Therefore, it is important that operators take full strokes to maximize pump performance.

- Decreases in stroke force or speed supplied by the operator can greatly decrease flow rate for some cases. However, pump designs optimized for low tank heights or low flow rates are robust and maintain consistent flow rates despite drops in stroke force or speed. Those pump designs are preferred for sustained operation or for use by elderly individuals.

- Experiments with the MoneyMaker Hip Pump revealed high agreement between the system-level efficiency predicted with the numerical model and that measured in the actual pump. These experiments also specifically validated the prediction that pump modifications can decrease cost by approximately 37% while maintaining performance. However, the predicted 88% increase in flow rate for a pump of the same cost has not been validated.

Pumps optimized for low flow rates (below 0.1 L/s) were robust across a variety of different conditions. These pumps were also capable of functioning at optimal performance for all tank heights. Further, these low flow pumps have small overall dimensions making them easily portable. For these reasons—robustness, versatility, portability — the low flow rate pump designs identified in this work are recommended for further development.

It is unclear if the volume-based objective function (which returned accurate results for low flow rates) can be generalized to other human-powered products. Similar comparisons should be made for other products in future work to assess the generalizability of this method to other human-powered products. Other future work should explore the interaction between modified use scenarios, and incorporate product modularity concepts to explore the development of several distinct pumps as a line of products with interchangeable components. In addition, more detailed optimization could be accomplished by utilizing finite computational approaches for computing fluid flow and stresses in the components of the pump. Finally, a greater understanding of operator fatigue should be incorporated into the optimization approach used here. This could be accomplished through data-driven models of human physiology or through direct experimentation in extended pumping episodes. Ultimately, this work demonstrates that the application of advanced engineering principles to global development practices can create low-cost, high-value products that benefit development organizations, businesses, and end users throughout the world.

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