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IMPROVING IRRIGATION IN REMOTE AREAS: MULTI-OBJECTIVE OPTIMIZATION OF A TREADLE PUMP

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ABSTRACT
Water-lifting technologies in rural areas of the developing world have enormous potential to stimulate agricultural and economic growth. The treadle pump, a human-powered low-cost pump designed for irrigation in developing countries, can help farmers maximize financial return on small plots of land by ending their dependency on rain-fed irrigation systems. The treadle pump uses a suction piston to draw groundwater to the surface by way of a foot-powered treadle attached to each suction piston. Current treadle pump designs lift water from depths up to 7 meters at a flow-rate of 1-5 liters per second. This work seeks to optimize the design of the Dekhi style treadle pump, which has gained significant popularity due to its simplicity. A mathematical model of the working fluid and treadle pump structure has been developed in this study. Deterministic optimization methods are then employed to maximize the flow rate of the groundwater pumped, maximize the lift height, and minimize the volume of material used for manufacturing. Design variables for the optimization included the dimensions of the pump, well depth, and speed of various parts of the system. The solutions are subject to constraints on the geometry of the system, the bending stress in the treadles, and ergonomic factors. Findings indicate that significant technical improvements can be made on the standard Dekhi design, such as increasing the size of the pump cylinders and hose, while maintaining a standard total treadle length. These improvements could allow the Dekhi pump to be implemented in new regions and benefit additional rural farmers in the developing world.

INTRODUCTION
Current statistics indicate that nearly one-half of the world's population live in poverty on less than $2 per day [1]. Although governments and non-governmental organizations have been working to decrease the extent of poverty in developing countries, the past sixty years has yielded only modest improvement [2]. Progress has largely occurred in urban areas that have ready access to markets, infrastructure, and power. Conversely, rural areas of the developing world have seen little to no improvement in quality of life or economic prosperity [2]. However, the growing use of a market-based approach to poverty alleviation, instead of an aid-based approach, is showing signs of success in both urban and rural areas. Market-based strategies focus on income-generation and the establishment of businesses or entrepreneurs to cooperatively finance development. This has the potential to create long-term financially sustainable solutions that exist after aid is discontinued. Market-based strategies often focus on the creation of a new good or service, assistance for a local business or entrepreneur, or the establishment of a supply chain to transport goods to consumers.

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Development efforts that aim to stimulate local entrepreneurship typically provide a combination of financing to start a business, technology to increase productivity, and education in business and technical areas [3-5]. These entrepreneurs often provide an essential resource that improves community development—food, clothing, medicine, power, or other goods and services. Yet the benefits of market-based poverty alleviation strategies extend beyond the target locality. It is estimated that the distribution of profits throughout supply chains has helped more than 17 million people transition out of poverty [6-10]. Examples of technologies delivered to entrepreneurs include water pumps, looms, commercial cooking stoves, farming equipment, and bread ovens. The observed success of such work has led to the rapid deployment of technology, and at times, the deployment has outpaced improvements that could have been realized through engineering design work. Additional applied research in engineering design can benefit many technologies targeted at poverty alleviation. This paper applies engineering optimization to explore design alterations to the treadle-pump, a human-powered water pump for irrigation. Used primarily in rural areas, treadle pump design can improve crop yields by up to 50% [11], and has demonstrated success in countries throughout Asia, Africa and the Americas [12-13].

BACKGROUND

The majority of rural poor are subsistence-level farmers with little or no supplemental income [13]. One of the few pathways to economic prosperity is improving the yield from a fixed plot of land. Reliable irrigation techniques have been shown to increase crop yields between 100%-400% [14]. The resulting increase in grain volume translates to increased sales and income, and allows farmers to cultivate higher-value crops, adopt new technologies, and increase financial returns. Despite the benefits of irrigation, too few farmers have a steady source of irrigation due to the financial limitations of acquiring commercial irrigation technologies. Although diesel pumps are effective for irrigation, the capital cost and fuel costs are too high for most poor farmers in the developing world. Pumps with low capital cost and little or no operating cost can help farmers maximize profits. Human-powered treadle pumps (Figure 1) increase the financial return on small plots of land compared to rain-fed irrigation systems [15]. Farmers using treadle pumps have been reported to earn an average of $100 in extra income per year [8].

Stepping up and down on the treadles actuates two pistons that create suction and draw groundwater to the surface. The current design of the treadle pump enables pumping of water from depths of up to seven meters and allows for a maximum flow-rate of five liter per second [16,17]. Yet several design challenges remain with this technology. Since the first treadle pump invented by the Norwegian engineer Gunnar Barnes in 1970, companies like International Development Enterprises (IDE), Kickstart and others have re-designed the treadle pump to serve a wider range of customers by adapting the technology to the geographic, environmental, economic and cultural requirements of customers. Kickstart recognized that groundwater is deeper in many African countries and modified a basic treadle design to achieve greater suction head [18]. This initiated the development of pressure pumps, which are able to access water from deeper wells and deliver water to greater heights. Such design changes have enabled Kickstart to expand their treadle pump sales in many different countries.

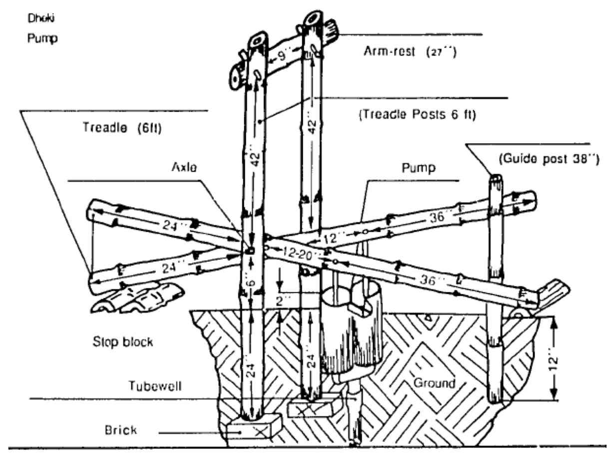

FIGURE 1: Dheki Pump (Real System) [Gunnar]

Recent work has investigated modular treadle designs that can be reconfigured with additional components to achieve increasingly higher performance pumps [19]. Higher performance modules can be purchased with additional income from the basic treadle design. The modular design allows the customer to make a three-stage investment to incrementally increase performance and reduce financial risks of buying the high-performance treadle pump outright. Wood's work seeks to optimize the three-stage investment in terms of affordability and income potential based on the performances of the three commercialized pumps by Kickstart. Multi-objective optimization was used to maximize the volume of water output and minimize cost of three modular investment stages for a constant water well depth.

This study applies optimization to improve the operating characteristics of a pump while minimizing volume of construction material—as an indicator of cost. Multi-objective optimization is applied to the Dekhi style pump designed by IDE. A wide range of design changes is analyzed in pursuit of a cheaper pump with greater marketability for low-income farmers.

APPROACH

This paper seeks to maximize pump flow rate and lift height, while minimizing the material usage of the pump. To accomplish this, the multi-objective problem was converted into a constrained parametric study. The optimization was performed with respect to the dimensions of the system and well depth, as well as the speed of various parts of the system. The solutions are subject to constraints on the geometry of the system, the bending stress in the treadles, and several human factors.

The following notation is utilized: a superscript T indicates a treadle dimension, a superscript P indicates a pump dimension, a superscript V indicates a rate or velocity, and a superscript R indicates a mass. Diagrams depicting the idealized system and the decision variables are provided in Figures 2, 3 and 4. Figure 2 shows the treadle during the downward (power) stroke and Figure 3 shows the treadle during the upward (return) stroke.

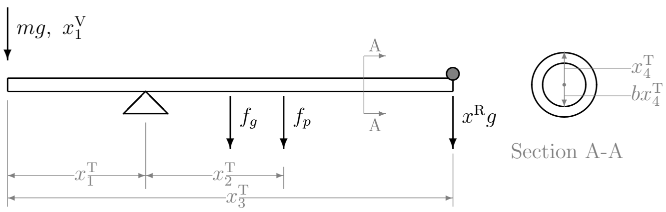

FIGURE 2: Treadle Dimensions and Forces During Power Stroke

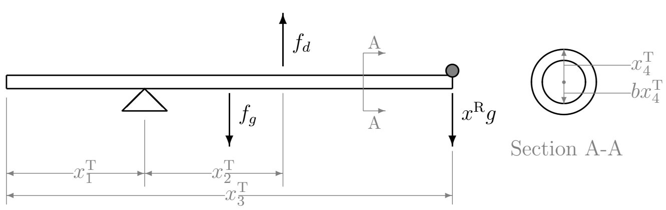

FIGURE 3: Treadle Dimensions, and Forces During Return Stroke

The variable x_1^{T} is the distance between the fulcrum and the operator's foot, x_2^{T} is the distance between the fulcrum and the pump, and x_3^{T} is the total length of the treadle. Section A-A shows the circular cross section of the treadle with the outer radius being the variable x_4^{T}. The step rate of the downward stroke is shown as variable x_1^{V}. Additionally, a mass at the end of the treadle ensures that treadle will return to its original position and it is shown in the Figures as the variable x_{R}. Figure 3 shows a diagram of the pump cylinder designed by IDE and also shows an idealized system of the pump cylinder. The variable x_1^{P} is the length of the cylinder, x_2^{P} is the radius of the cylinder, x_3^{P} is the radius of the hose, and x_4^{P} is the length of the hose. Last, variables x_2^{V} and x_3^{V} are velocity of the cylinder during the power stroke and return stroke, respectively.

The material usage of the pump is analogous to the volume of material used. This quantity is calculated as:

$$f(x) = \left[\left(x_4^{\mathrm{T}}\right)^2 - \left(bx_4^{\mathrm{T}}\right)^2\right]x_3^{\mathrm{T}} + 2\pi\left(x_2^{\mathrm{P}}x_1^{\mathrm{P}}t_{\mathrm{CYL}} + x_3^{\mathrm{P}}x_4^{\mathrm{P}}t_{\mathrm{HOSE}}\right) + \pi\left(x_2^{\mathrm{P}}\right)^2 t_{\mathrm{PIST}}$$

The parameters t_{CYL}, t_{HOSE}, and t_{PIST} are the wall thickness of the cylinder, the hose, and the pump piston, respectively.

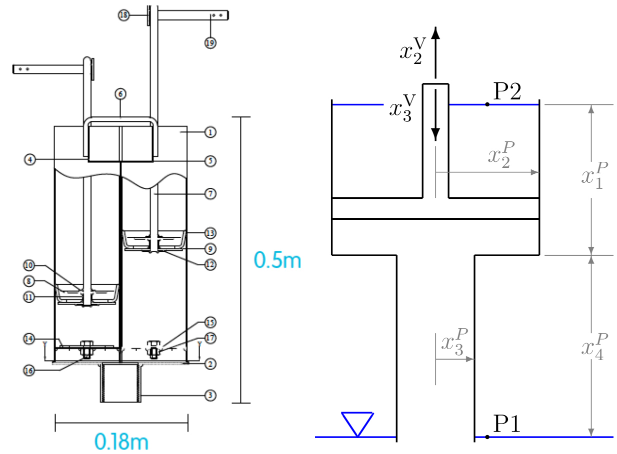

FIGURE 3: Actual pump cylinder (left), and idealized pump dimensions (right)

The optimization problem has 13 constraints and 12 variables. Table 1 shows the constraints imposed on the problem. There are 8 inequality constraints, and 5 equality constraints, so the problem has at most 8 degrees of freedom. Constraints g_4, g_6, g_7, h_1 and h_4 were formulated specifically to facilitate the solution of the fluid system. Another inequality constraint g_1 was formulated to ensure that the treadle does not break during operation. Constraints g_2, g_5, g_8, and h_2 were implemented to ensure that the operation of the pump is comfortable for the operator (human factors). Constraint g_3 was implemented simply to ensure that the total length of the treadle is at least the distance between the operator's foot and the pump. Last, constraints were placed on the pump lift height and flow rate to facilitate the constrained parametric study (h_3 and h_5, respectively).

The values θ_{MAX} and s_{MAX} were values that approximately ensured comfortable pump operation. The value for t_{MIN} was set according to standard treadle widths for current pumps. The value for y_{MAX} was set to a value provided in [20]. Each of these variables was subjected to a sensitivity analysis, discussed later in this paper. A full list of the model parameters used in this paper is shown in Table 2.

This analysis utilized several simplifying assumptions. First, the mass of a generic user was selected (the mass of the user is later subjected to sensitivity analysis). Second, fluid analysis was performed at steady state as a simplification of moving discrete volumes of water with the treadles.

The steady-state pump model was validated by comparing the modeled flow rate against the manufacture's specifications. Using the model presented here, a flow rate of 0.0022 m^3/s was calculated for the Dekhi treadle pump with a lift height of 6 m. This value was 10% higher than the manufacturer's specifications of 0.0020 m^3/s at the same lift height [17].

TABLE 1: Inequality and Equality Constraint Functions

Constraint	Description
$g_1(\mathbf{x}) = \sigma - \sigma_{\text{MAX}} \leq 0$	Stress in treadles (Pa)
$g_2(\mathbf{x}) = t_{min} - 2x_4^{\text{T}} \leq 0$	Width of treadles (m)
$g_3(\mathbf{x}) = x_1^T + x_2^T - x_3^T \leq 0$	Treadle length dimensions (m)
$g_4(\mathbf{x}) = x_4^P + x_1^P - \frac{f_p}{\rho_w g\pi(x_2^P)^2} \leq 0$	Minimum force to operate (N)
$g_5(\mathbf{x}) = x_1^{\text{V}} - s_{\text{MAX}} \leq 0$	Max step speed (human) (Hz)
$g_6(\mathbf{x}) = x_1^{\text{V}} - \frac{x_2^{\text{V}}}{x_1^P} \leq 0$	Max step rate (mechanical) (Hz)
$g_7(\mathbf{x}) = x_2^{\text{V}} - x_3^{\text{V}} \leq 0$	Adequate speed of return (m/s)
$g_8(\mathbf{x}) = y_{\text{MAX}} - x_1^{\text{T}} \sin(\theta_{\text{MAX}})$	Maximum angle of treadle $(deg.)$
$h_1(\mathbf{x}) = (x_4^P + x_1^P) + \frac{(x_2^{\text{V}})^2}{2g} + \frac{10.67x_4^{\text{P}} q_{\text{I}}^{1.85}}{c_{\text{HW}}^{1.85}(2x_3^{\text{P}})^{4.87}} + \frac{10.67x_1^{\text{P}} q_{\text{I}}^{1.85}}{c_{\text{HW}}^{1.85}(2x_2^{\text{P}})^{4.87}} - \frac{f_p}{\rho_w g\pi(x_2^P)^2} = 0$	Energy conservation in fluid (m)
$h_2(\mathbf{x}) = x_1^{\text{T}} x_1^{\text{P}} - y_{\text{MAX}} x_2^T = 0$	Maximum step size related to cylinder height (m^2)
$h_3(\mathbf{x}) = h_{\text{TARGET}} - x_4^{\text{P}} = 0$	Required lift height (m)
$h_4(\mathbf{x}) = (x_3^{\text{V}})^2 - \frac{2f_d}{c_d a \rho_w} = 0$	Equation for speed of fall $(m/s)^2$
$h_5(\mathbf{x}) = q_{\text{TARGET}} - \pi x_1^{\text{V}} x_1^{\text{P}} (x_2^{\text{P}})^2 = 0$	Required flow rate (m^3/s)
$\mathbf{x}^{\text{LB}} \leq \mathbf{x} \leq \mathbf{x}^{\text{UB}}$	Simple bounds
$\mathbf{x} \in \mathbb{R}^{13}$	Real valued

TABLE 2: Model Parameters

Symbol	Description	Units
m	Mass of operator	kg
ρ_{T}	Density of treadle (bamboo)	kg/m^3
σ_{MAX}	Treadle tensile strength (bamboo) [21]	MPa
t_{MIN}	Minimum treadle width	m
y_{MAX}	Maximum step height [20]	m
ρ_{W}	Density of water	kg/m^3
s_{MAX}	Maximum step rate	Hz
c_{HW}	Hazen-Williams factor[22]	—
c_{D}	Coefficient of drag	—
q_{TARGET}	Target flow rate	m^3/s
h_{TARGET}	Target lift height	m
t_{CYL}	Thickness of cylinder	m
t_{HOSE}	Thickness of hose	m
t_{PIST}	Thickness of piston	m
θ_{MAX}	Maximum deflection angle of treadles	$deg.$
b	Ratio of inner radius to outer radius[23]	—

TABLE 3: Simple Bounds

Variable	Lower	Upper	Units
x_1^{T}	0.00	2.00	m
x_2^{T}	0.00	2.00	m
x_3^{T}	0.00	2.50	m
x_4^{T}	0.00	0.15	m
x_1^{P}	0.00	1.00	m
x_2^{P}	0.00	0.15	m
x_3^{P}	0.00	0.10	m
x_4^{P}	0.00	20.00	m
x_1^{V}	0.00	3.00	Hz
x_2^{V}	0.00	20.00	m/s
x_3^{V}	0.00	20.00	m/s
x^{R}	0.00	100.00	kg

OPTIMIZATION STUDY

The optimization study entailed solving a variety of combinations of flow rates and lift heights. All variables were scaled to their simple bounds prior to implementation in order be able to compare constraint values later on (Table 3).

In addition, all functions were scaled so that they returned values on the order of 1. For each case, the required pump lift was set (either to 3, 6 or 12 meters), as well as the required flow rate (to a range of values between 0.0001 m^3/s and 0.012 m^3/s), and the pump was optimized for minimum material usage (volume).

Each case was solved using the `fmincon` function in MATLAB. The Sequential quadratic programming (SQP) algorithm was used with merit-function line search and quasi-Newton Hessian updating. This algorithm was chosen because many of the functions in this problem are quadratic. Additionally, the SQP algorithm is robust to undefined function evaluations, which aided convergence in our problem. 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 completed several times with randomized starting points for each case to increase the likelihood that global optima were found.

This is a case of multiobjective optimization. Therefore, there does not exist a single, optimal solution. Instead, we turn two of the objectives (specifically flow rate and lift height) into equality constraints, and minimize with respect to mass. This allows us to resolve points along the Pareto front. This Pareto set is depicted graphically in Figure 4. The existing Dekhi treadle pump design is also shown in Figure 4.

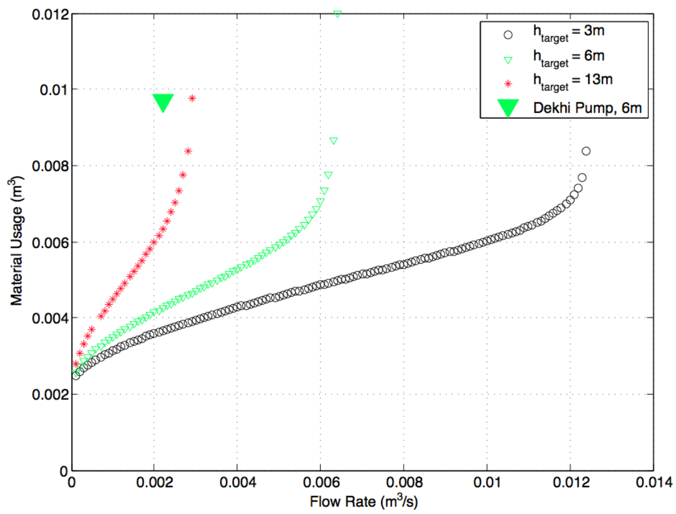

FIGURE 4: Pareto Fronts from Optimization Study

TABLE 5: Lagrange Multipliers

Constraint	Function Value	Lagrange Multiplier
g_1	-0.2144	0
g_2	0	0.0757
g_3	0	0.0318
g_4	-0.0075	0
g_5	0	0.0014
g_6	0	0.2693
g_7	0	0.0010
g_8	0	0.0081
h_1	0	0.0004
h_2	0	0.0303
h_3	0	-0.0916
h_4	0	0.2526
h_5	0	-0.3373

TABLE 4: Representative Designs

	Current Design $H : 6m$ $Q : 0.020m^3/s$ $V : 0.0097m^3$	Optimal Design $H : 6m$ $Q : 0.020m^3/s$ $V : 0.0043m^3$	Design A $H : 3m$ $Q : 0.0100m^3/s$ $V : 0.0060m^3$	Design B $H : 3m$ $Q : 0.020m^3/s$ $V : 0.0036m^3$	Design C $H : 3m$ $Q : 0.0120m^3/s$ $V : 0.0071m^3$	Design D $H : 1.9m$ $Q : 0.0025m^3/s$ $V : 0.0036m^3$	Design E $H : 15m$ $Q : 0.0025m^3/s$ $V : 0.0098m^3$
x_1^{T}	0.400m	0.700m	0.700m	0.700m	0.700m	0.700m	0.700
x_2^{T}	0.200m	0.0987m	0.192m	0.095m	0.178m	0.105m	0.087m
x_3^{T}	2.000m	0.799m	0.892m	0.795m	0.878m	0.805m	0.787m
x_4^{T}	0.035m	0.038m	0.038m	0.038m	0.038m	0.038m	0.038m
x_1^{P}	0.030m	0.049m	0.038m	0.047m	0.089m	0.052m	0.043m
x_2^{P}	0.045m	0.084m	0.128m	0.082m	0.146m	0.087m	0.096m
x_3^{P}	0.038m	0.011m	0.029m	0.008m	0.045m	0.008m	0.027m
x_4^{P}	6m	6m	3m	3m	3m	1.9m	15m
x_1^{V}	2Hz	2Hz	2Hz	2Hz	2Hz	2Hz	2Hz
x_2^{V}	0.099m/s	0.099m/s	0.192m/s	0.095m/s	0.178m/s	0.105m/s	0.087m/s
x_3^{V}	0.099m/s	0.099m/s	0.192m/s	0.095m/s	0.178m/s	0.105m/s	0.087m/s
x^{R}	0.00kg	3.11kg	1.63kg	3.25kg	1.75 kg	2.93kg	3.55kg

According to our model, all designs on the Pareto front improve on the Dekhi pump in some way. Further, an inspection of the Pareto designs themselves indicated the geometry nature of the improvements on the Dekhi pump. Representative designs that indicate these improvements are provided in Table 4. Some of these improvements include:

- Shorten the treadle total length.
- Increase the cylinder pump diameter.
- Decrease the hose diameter.

Several design relationships were identified by exploring the effect of input parameters on the optimal designs. The treadle dimensions remained largely unchanged for any combination of flow rate and lift height and increasing the required flow rate resulted in larger cylinder and hose dimensions (variables x_1^{P}, x_2^{P}, x_3^{P}). To illustrate this trend, representative low flow rate and high flow rate designs are provided in Table 4 as Design B and Design C. Increasing the required lift height, however, primarily increased the hose diameter (x_3^{P}). To illustrate this trend, representative low lift height and high lift height designs are shown in Table 4 as Design B and Design E.

Further discussion can be completed by examining a single solution on the Pareto front. This is the solution corresponding to a flow rate of 10 L/s and a lift height of 3 m. The optimal pump for this design has a material usage of 0.006 m^3 shown in Table 4 as Design A. Many of the constraints are active at this solution. This means that the inequality constraints are behaving as equality constraints, thus dictating the design changes. Table 5 provides a list of the constraints, their values at the solution, and the Lagrange multiplier associated with each. Interestingly, g_1 is inactive, indicating that the treadles are stronger than necessary. This constraint is dominated by g_2, which places a minimum width on the treadles. The following constraints are practical and active: g_2, g_5, g_8. Practical constraints are simple reasonable assumptions about the feasible domain of the design variables. All of the practical constraints have relatively small Lagrange multipliers suggesting that, in general, small perturbations do not have a large effect on the objective value of the function. However, two natural constraints (g_6 and h_4) have large associated multipliers. This suggests that small change in the fall-speed relationship or the step-speed relationship could have a significant impact on the optimal design.

The Karush–Kuhn–Tucker (KKT) conditions can then be checked to ensure that regularity and necessary conditions are satisfied and thus a local optimum had been found. According to the SQP algorithm, the value of the gradient of the Lagrangian at the solution is 3.58×10^{-7}. This is sufficiently close to zero to consider that the KKT conditions are satisfied and a stationary solution has been found. An inspection of Table 5 reveals that the feasibility condition is satisfied, $h(x)=0$ and $g(x)\leq 0$ (to within a small error tolerance). Further, we see that all Lagrange multipliers associated with inequality constraints are positive, thus the positivity condition is satisfied. All inactive constraints have a Lagrange multiplier of 0, satisfying the complementarity condition. Consequently, this solution is a KKT point.

PARAMETRIC SENSITIVITY ANALYSIS

Eight of the thirteen model parameters were chosen for sensitivity analysis. The five parameters left absent included scientific constants and pump design features— t_{CYL} and t_{HOSE} —that did not make practical sense to vary without considering other constraints such as the material properties of the cylinder. Figure 5 shows that the solution is fairly robust to variations in the parameters. Though some variations in parameters in Figure 5 show large changes in volume, the objective function, the practicality of such parameter changes may not make the corresponding volume changes feasible.

The bamboo strength (σ_{MAX}) and drag coefficient (C_d), do not have any effect on the objective value. Changes in the remaining parameters that relate to the geometry of the pump show a near linear relationship with respect to the objective function. Intuitively, the linear relationship is expected since a direct change to the geometry will change the volume of the system. Parameters including mass of the operator (m), step height (y_{MAX}), step rate (s_{MAX}), and deflection of treadles (θ_{MAX}) show a non-linear change in the material volume value as the parameters vary. This indicates that parameters associated to consumer size and mass have a stronger effect on the material volume than the selected parameters related to pump geometry. In general, it appears that the optimal design is most sensitive to variations in the minimum treadle width, and the cross-sectional characteristics of the treadles.

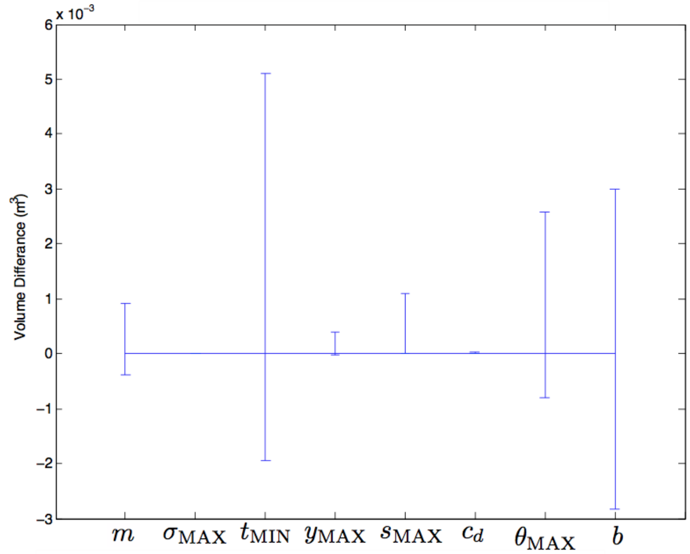

FIGURE 5: Sensitivity of Optimal Solution to Parametric Variations

CONCLUSIONS AND FUTURE WORK

This work created a model of the Dekhi style treadle pump. This model took into consideration structural aspects of the treadles, the fluid operation of the pump itself, and ergonomic limitations on the operation of the pump. Deterministic optimization methods were then used to optimize this model with respect to material usage, flow rate, and lift height. This resulted in a set of minimal-material designs for varying combinations of flow rate and lift height. In addition, inspection of this set revealed geometrical trends that could be utilized to provide design heuristics.

Perhaps most importantly, these results indicate that there is substantial room to improve the current design of the Dekhi treadle pump. Shortening the treadle total length, increasing the cylinder pump diameter, and decreasing the hose diameter are some of the main design changes that reduce the material volume used for manufacturing. An analysis of the active constraints at one of the optimal points indicates that width of the treadles, maximum step speed of the operator and the maximum angle of the treadle are important considerations in the optimal design of the pump. In addition, the results indicate that pump designs can be tuned for optimal operation at a specific flow rate and lift height by changing only a few parameters. In order to vary the optimal flow rate of the pump, only the hose diameter need to be changed substantially. Similarly, to vary the optimal lift height of the pump, only cylinder and hose dimensions need to be changed substantially.

Future work will seek to refine the model by reducing assumptions, and thereby allow exploration of detailed design decisions that involve the selection of materials and manufacturing techniques.

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