Proceedings of the ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference
IDETC/CIE 2017
August 6-9, 2017, Cleveland, Ohio, USA

DETC2017-67581

AN ASSESSMENT OF VILLAGE DRILL SUSTAINABILITY, WITH RECOMMENDATIONS

Andrew T. Pack
Graduate Research Assistant
Dept. of Mechanicall Engineering
Brigham Young University
Provo, Utah 84602
Email: andrewpack@byu.edu

Christopher A. Mattson*
Associate Professor
Dept. of Mechanical Engineering
Brigham Young University
Provo, Utah 84602
Email: mattson@byu.edu

ABSTRACT

Sustainability is commonly broken into three categories: economic, environmental, and social. For products, there is a need for design tools that allow decision makers to handle the tradeoffs between each of these three pillars of sustainability. This paper simultaneously assesses all three pillars of sustainability for the Village Drill, a machine used to dig water wells in rural areas around the world. Using data and methods from Mattson et al. [1, 2] relationships are developed between the drill's design parameters and key sustainability issues. These relationships are used to evaluate the sustainability of the current drill design as well as any alternatives. One million random sets of drill parameters are generated and the resulting drill alternatives are evaluated. A three-dimensional design space for the sustainability of the drill is found and recommendations are given with potential for improvements in each pillar of sustainability.

1 INTRODUCTION

Sustainability has recently become one of the most popular goals for businesses and governments [3]. In fact, the United Nations Environmental Programme (UNEP) has designated sustainability as the main goal for the future development of human kind [4]. We are fast approaching a point where considering sustainability will no longer be optional, but will be a requirement imposed by key stakeholders and legislative policies [5]. A common way to handle sustainability is to divide it into three categories; economic, environmental and social sustainability [6]. This is frequently referred to as the triple bottom line [7, 8], or the three pillars of sustainability [9]. For product development, various methods have been developed for individually handling each of these categories [10, 11]. Others have sought a combined approach to create a complete analysis of a *business* or *civil policy* [12, 13], but only a few attempts and methodologies exist that evaluate the full sustainable impact of a *product* [6, 14, 15].

Designers have previously been successful in applying at least one aspect of the triple bottom line to a product, but optimal decisions in sustainability can only be made when all three impact areas, and their tradeoffs, are considered together [16]. Some argue that a comprehensive analysis of sustainability should be the goal of all product development [4].

The purpose of this paper is to simultaneously assess all three pillars of sustainability for the Village Drill, a manually operated drill that creates boreholes for water wells in developing countries. The drill was designed by Brigham Young University in 2012 under the direction of WHOlives.org. It is unique because it uses human power and is easy to disassemble for transportation to a job site. This allows the drill to reach villages areas that are unable to create or afford bore holes using traditional drilling rigs. The drill is currently being used to provide clean drinking water to hundreds of thousands of individuals in parts of Africa, Asia, and South America [2]. Now, using data from the

*Address all correspondence to this author.

drill's first five years on the market, we consider its sustainability and explore possible design improvements.

A case study by Mattson et al. [2] collected data on the Village Drill. This study discovered, among other things, how much water and how many jobs the drill provided to the people in areas where it was being used. This data mainly focused on the economic and social impact of the drill.

Mattson et al. [1] also presented a method to create a three-dimensional design space for a given product that visualizes potential tradeoffs between the three pillars of sustainability. The method, which can be used for any product, seeks to establish mathematical relationships between a product's independent parameters and pertinent sustainability issues. These relationships are then aggregated into sustainability scores for each plausible design and are plotted in a three-dimensional design space.

This paper combines these two recent contributions by Mattson et al. [1,2] to show a more holistic view of the Village Drill's triple bottom line. The results shown in section 3 provide a three-dimensional design space for the sustainability of the Village Drill. We also provide a set of design alternatives that represent key points in the design space.

2 METHODOLOGY

We now combine the 5-step process presented by Mattson et al [1] with data collected in the Village Drill case study [2]. The process operates under the assumption that the drill will be redesigned with a simlar concept to what is currently being produced (as opposed to producing a drill with a completely new geometry and mechanisms), but the development team will have freedom to change the product's dimensions and a few select features. The general concept that will be modified for sustainable product development is the Village Drill, shown in Fig. 1.

Drill Operation: The current drill design is operated by 3-4 wheel operators, a slurry pump operator, and a winch operator. The drill is disassembled and transported by truck, cart or by hand to a new drill site. The current assembly consists of 6 assembly pieces for the main structure, 17 pieces to build the wheel and spokes, and over 80 lengths of pipe just under 1 meter long for the drill string. The wheel operators drill into the ground by continuously rotating the wheel assembly while a winch operator keeps tension on the drill string. This tension in the drill string reduces the required torque needed to drill and without it the drill bit would compress into the ground and would require the wheel operators to exert a much higher force on the wheel. After a full length of pipe has been drilled into the ground the team stops the wheel rotation and attaches another length of pipe to the drill string. They then re-attach the square kelly bar on the other end of the pipe and continue drilling. This process is continued until the drill team has reached the desired depth for the well. The winch is also used to retract the pipe at the end of the drilling process. The slurry pump is used while drilling to inject a water/bentonite mixture that is used to remove cuttings from the hole and seal the hole walls.

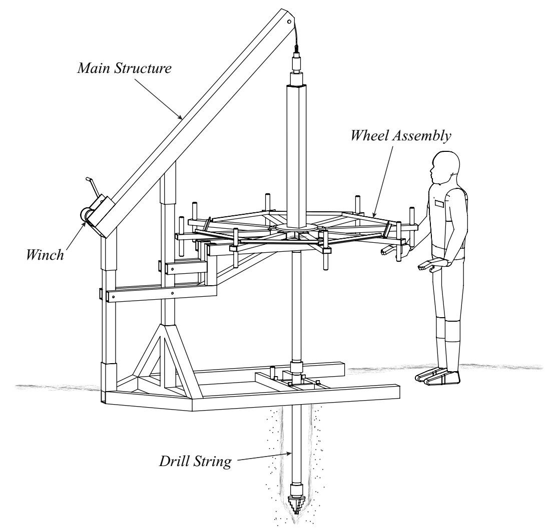

FIGURE 1. THE GENERAL DRILL CONCEPT, WITH DRILL PIPE ATTACHED.

2.1 Step 1: Identify sustainability issues

The following sustainability issues have been chosen to represent the design space for the Village Drill.

1. Economic Sustainability
   (a) cost to produce the drill*
   (b) selling price of the drill*
2. Environmental Sustainability
   (a) manufacturing process emissions
   (b) shipping emissions
   (c) ongoing emissions from drill operation
3. Social Sustainability
   (a) number of people served water*
   (b) jobs created*
   (c) potential for driller injury
   (d) possible market penetration*
4. Design Constraints
   (a) structural safety
   (b) geometric feasibility

*Indicates a measure for which data is available

This list represents key measures that are important to WHOlives.org, users of the product, and other stakeholders. Several more factors could have been considered in each category of the triple bottom line. Undoubtedly the more detailed and comprehensive we make the list the more accurately we can characterize the design space. A trade-off must be made by the design team between developing a high-fidelity expensive model or, developing a low-fidelity inexpensive model.

2.2 Step 2: Link issues to parameters

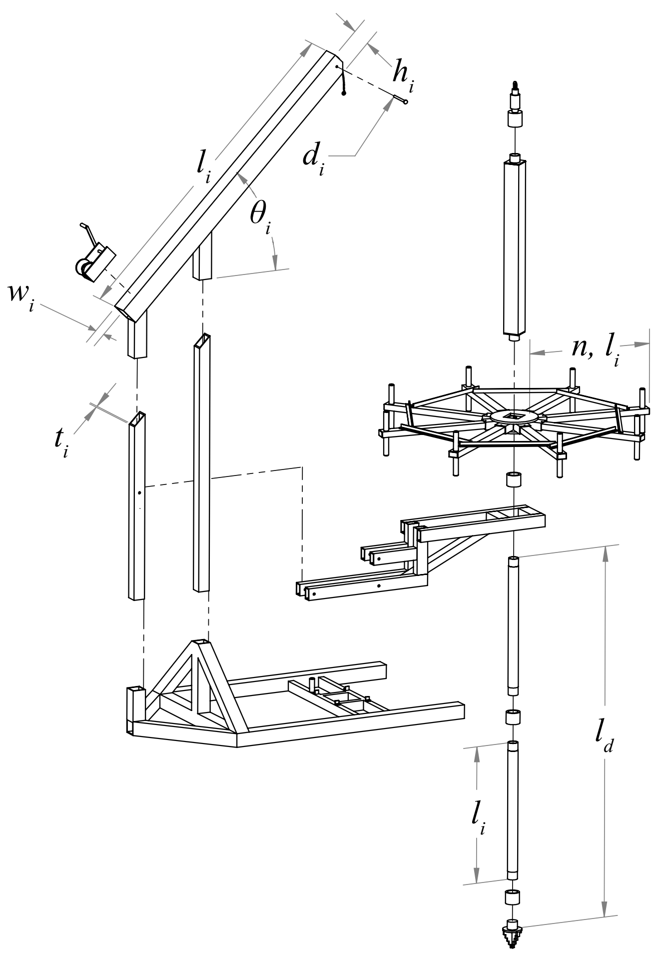

FIGURE 2. EXAMPLES OF A FEW OF THE INDEPENDENT PARAMETERS FOR THE VILLAGE DRILL.

Fig. 2 shows the basic parts of the Village Drill. We have chosen 22 independent parameters which include the basic geometric dimensions (l, w, h, t) for most structural members, the angle (θ) of the cantilever beam, the number of spokes (n) and the maximum depth the drill can achieve (l_d). Table 1 shows each of the drill's parameters with corresponding upper and lower bounds used for design space exploration. We will use these parameters and seek to find their relationship to the sustainability issues identified in step 1.

Using a combination of product data and assumptions, we can discover relationships between the drill's parameters and the sustainability issues identified in section 2.1. The process used to do this is outlined in the following sections. Most relationships are based on data from Mattson et al. [2] or WHOlives.org directly. Other relationships use assumptions that are discussed more fully in the following sections.

2.2.1 Cost to produce the drill The cost to produce the drill is partially dependent on the amount of material in the final drill design (including scrap), the amount of welding that is needed for assembly, and the cost of each piece of hardware required for the drill. Specifically, the total cost (C_{tot}) is

$$C_{tot} = C_{\mathrm{mat}} + C_{\mathrm{wld}} + C_{\mathrm{hdwr}} \tag{1}$$

where C_{mat} is the material cost, C_{wld} is the cost to weld the individual pieces into the final assembly and C_{hdwr} is the cost of the nuts, bolts, washers, etc. These are calculated as

$$C_{mat} = \sum_{i=1}^{n} A_i l_i \rho C_{\mathrm{i}} \tag{2}$$

where A_i and l_i are the cross-sectional area and length of the i-th member, respectively. ρ is the material density, and C_i is the cost per gram of the selected material for the i-th member. C_{wld} is calculated as

$$C_{wld} = D_{wld} C_{wld} R_{wld} \tag{3}$$

where D_{wld} is the weld perimeter, C_{wld} is the welding cost per hour, and R_{wld} is the weld rate. Because the basic design of the drill is static we assume the number of welding locations will not change, only the amount of welding required at each location.

2.2.2 Selling price of the drill WHOlives.org currently sells the drill for 18,000 USD [2]. Their current marketing strategy does not allow them to adjust the selling price based on fluctuations in the cost of goods sold. Because their goal is to bring social benefit to impoverished areas they have decided, for the time being, to hold the selling price at 18,000 USD. They may increase the selling price of the drill in certain circumstances, but for this analysis we will keep the selling price constant. Therefore, the equation for P, the selling price of the drill, is

$$P = 18000 \tag{4}$$

TABLE 1. EACH OF THE DRILLS 22 INDEPENDENT PARAMETERS ARE LISTED WITH THEIR CORRESPONDING UPPER AND LOWER BOUND.

Variable	Description	Lower Bound	Upper Bound
l_i	Length of the *i*-th beam	l_1 = 500 mm l_2 = 1000 mm l_3 = dependent l_4 = 500 mm	l_1 = 3500 mm l_2= 1500 mm l_3 = dependent l_4 = 3500 mm
w_i	Cross-sectional width of the *i*-th beam (4 beams total)	10 mm	320 mm
h_i	Cross-sectional height of the *i*-th beam	10 mm	320 mm
t_i	Cross-sectional thickness of the *i*-th beam	1 mm	17.5 mm
x_{dis}	Distance between the two upright supports	250 mm	1050 mm
θ	Angle of the top cantilever beam	0°	75°
n	Number of spokes on the wheel assembly	3	12
l_{spk}	Length for one spoke on the wheel assembly	100 mm	2200 mm
l_{pipe}	Length of one section of pipe in the drill string	200 mm	1500 mm
l_d	Total potential length of the drill string	42 m	73 m
d_p	Diameter of pulley pin used at the top of the cantilever beam	2 mm	20 mm

2.2.3 Carbon footprint We have no data on the Village Drill's environmental impact, therefore we will have to turn to other sources to estimate its impact. One of the many possible indicators for environmental impact is carbon emissions. According to the International Organization of Standardization (ISO) the carbon footprint of products (CFPs) should consider key stages in its life cycle, including "raw material acquisition, production, distribution, [and] use" [17]. Following this standard, we have summarized the drill's environmental impact to include manufacturing, shipping, and ongoing emissions.

The US Environmental Protection Agency publishes best practices and useful data to calculate a product's carbon footprint [18]. A general equation they recommend using is

$$\varepsilon = E_f A \tag{5}$$

where ε is the emissions, A is the activity data (e.g., fuel consumed, or material input) and E_f is an emission factor that calculates the emissions based on the activity [18]. The EPA also provides emission factors for most common processes and is the source for all emission factors used in this model. These emission factors will generate emissions in grams of CO_2.

Manufacturing emissions: The major carbon contribution for manufacturing is in procuring and forming the steel. $E_{f,stl}$, as defined by the EPA, uses the total mass of steel needed in the product to calculate the carbon footprint due to acquiring and forming the steel. A second major process in drill manufacturing is the welding required for assembly. An emission factor, $E_{f,wld}$, was used for welding which calculates emissions based on the total amount of electrode consumed. The total emissions for manufacturing the drill is

$$\varepsilon_{mfg} = E_{f,stl} \sum_{i=1}^{n} m_i + E_{f,wld} \sum_{i=1}^{n} p_{w,i} \tag{6}$$

where m_i is the mass of the *i*-th member and $p_{w,i}$ is the total weld perimeter required on the *i*-th member.

Shipping emissions: Vehicles used for shipping typically have relatively low fuel efficiency and have higher carbon emissions. The EPA has an emission factor for light duty trucks used in shipping. The relationship used for calculating emissions due to shipping is

$$\varepsilon_{shp} = D_{shp} E_{f,shp} m_t \tag{7}$$

where m_t is the total mass of the drill in metric tons, and D_{shp} is the furthest distance, in kilometers, the drill may be shipped from the factory. WHOlives.org ships the village drill from a factory in Kenya when the destination is within 2000 km of that factory, therefore, $D_{shp} = 2000$.

Ongoing emissions: The drill design implements a slurry pump used to push a water/bentonite mixture down the drill string to assist in the drilling process. This pump uses a 3.7 kW (5 hp) motor and its emissions are calculated as

$$\varepsilon_{\infty} = E_{f,pmp} d_{life} n_{bpm} f \tag{8}$$

where f is the amount of fuel, in liters, required to drill one bore hole and $E_{f,pmp}$ is an emission factor for the pump based on the number of liters of fuel the pump uses. The terms d_{life} and n_{bpm} refer to the life of the drill in months and the average number of holes a drill will make in a month. For the purpose of this analysis a drill life of 10 years is assumed.

2.2.4 Number of people served

Mattson et al. [2] have also shown that the number of people who are served water is linearly proportional to the rate at which a drill can produce a bore hole. The measure they use is the number of boreholes produced per month n_{bpm}. There are many complex factors that determine the actual number of holes produced, many of which are beyond what the drill design can influence. The two drill parameters that influence the hole production rate are the time it takes to drill a hole and the operating costs per hole. The expression for number of people served can be written as

$$N_{ppl} \propto n_{bpm} \tag{9}$$

and

$$n_{bpm} \propto \frac{(1-\hat{t}_{pb}) + (1-\hat{C}_{op})}{2} \tag{10}$$

where t_{pb} is the average time it takes to drill one hole, and C_{op} is the operating cost to produce one bore hole, both variables have been normalized. Proportionalities are used here because the number of people who are served water is not equal to the number of boreholes produced each month, nor are the number of holes produced each month equal to the amount of time it takes to drill one bore hole. Instead we do know that if the time it takes to produce one bore hole decreases, then the number of boreholes produced each month will increase, and the number of people impacted will similarly increase [2].

Normalization for $\hat{t}_{pb}$ and $\hat{C}_{op}$, and for normalized variables in future sections, is done after results have been found for each drill design in the population. The data is then normalized between 0 and 1 using the maximum and minimum values. Section 2.4 will discuss the method used for generating the model population.

The parameters of the drill are closely tied to both elements of equation 10. The time it takes to drill a borehole is dependent on the number of operators, the rotation rate (RPM) of the wheel and the number of stops required by the team to attach additional drill pipe to the drill string. The drill time equation, in minutes, is

$$t_{pb} = f_{mud}\left(\frac{l_d}{\overline{RPM} * R_{c,soil}}\right) + f_{rock}\left(\frac{l_d}{\overline{RPM} * R_{c,rock}}\right) + n_{stop} t_{stop} + t_{setup} \tag{11}$$

where l_d is the depth of the cut, R_c is the cut rate in millimeters per rotation and is provided by WHOlives.org. n_{stop} and t_{stop} are the number and length of each stop respectively, and t_{setup} is the time taken to assemble the drill at the well site before drilling begins. For reference, additional equations and constants used to calculate the borehole drill time are given.

$$P = \frac{\overline{T} * RPM}{9.55} \Rightarrow RPM = \frac{9.55 * kW}{\overline{T}} \tag{12}$$

$$\overline{T} = 170\ Nm \tag{13}$$

$$kW = 0.15 n_{op}{}^{\dagger} \tag{14}$$

$$R_{c,soil} = 2.73\ mm/rot \tag{15}$$

$$R_{c,rock} = 1.176\ mm/rot \tag{16}$$

$$t_{stop} = 5\ min \tag{17}$$

$$t_{setup} = n_{parts}{}^{\ddagger} \tag{18}$$

The cost for operation (C_{op}) considers fuel cost for the slurry pump and worker wages. The equation can be expressed as

$$C_{op} = 0.0083 t_{pb} C_{fuel} + N_{jobs} W_{labor} \frac{t_{pb}}{60} \tag{19}$$

where C_{fuel} is the cost of fuel and W_{labor} is the labor rate. The number of jobs (N_{jobs}) that the village drill provides is a social measure in and of itself and is discussed in more detail in the next section.

2.2.5 Jobs created

The number of jobs that the drill creates can be expressed as

$$N_{jobs} = n_{op} + 2 \tag{20}$$

† Number of required wheel operators. Operators are able to produce 0.2 HP (.15 kW) each [19]

‡ assuming one minute per part for assembly

The drill needs two workers in addition to the wheel operators for each job. The extra people are required to monitor the slurry pump and operate the winch. This also allows the team to take shifts operating the wheel versus the winch or pump. The number of operators can be expressed as

$$n_{op} = \begin{cases} 1 & \frac{0.9\pi d_w}{1.2} \leq 1 \\ \frac{0.9\pi d_w}{1.2} & \frac{0.9\pi d_w}{1.2} > 1 \end{cases} \tag{21}$$

$$d_w = 2l_{spk} + 104 \tag{22}$$

where d_w is the diameter of the wheel. This equation indicates that 90% of the wheel circumference is available for operators to use and each operator requires 1.2 meters along the perimeter of the wheel assembly to operate the drill. The other 10% of the wheel is unavailable space for operation because this is where the base structure attaches to the wheel. This equation is conditional because we will assume that there will always be space for at least 1 operator to turn the wheel. If the second conditional equation is true, then its value is rounded down to the nearest integer.

2.2.6 Risk of injury

Injury is an inherent risk found in all machinery, especially machines that require such close human contact. That injury negatively effects the social impact of the drill. We have, in conjunction with WHOlives.org, identified 4 features of the drill that may potentially cause injury. They are; (i) the number of stops required during operation, (ii) the potential for the cable to snap, (iii) exposed spoke ends, and (iv) excessive force required to operate. Injury, or risk, "may be defined as the measure of probability and severity of an unwanted event" [20]. We use the Injury Severity Score (ISS) as developed by Baker et al. [21] to model severity on a scale of 1 to 6 (minor to maximal/untreatable). Probabilities have been based on data from WHOlives.org.

Required stops: With the current drill design, the team will drill for about 10 minutes then stop to add another pipe length to the drill string. During this process a few situations arise that could cause injury. First, the coupler used to attach pipes to each other has sharp edges that could cause cuts or abrasions. Second, the nature of the process means there are heavy sections of pipe being handled. Any time heavy pieces of equipment are being moved you have a potential for pinching, wedging, muscle strain, etc. The model for injury during drill stoppage is expressed as

$$I_{stop} = \rho_1 S_1 n_{stops} \tag{23}$$

where n_{stops} is the number of stops required during one drill job and ρ_1 is the probability of injury occurring and S is the severity of injuries that may occur. Most injuries here will be minor (a 1 on the ISS) but it is likely that injury severity up to 2, moderate, may be experience. We used $S_1 = 2$ to ensure the most severe cases would be considered.

Cable Failure: The cable has been included in this model because the event of a cable failure often introduces an unknown and dangerous situation, especially when the cable is under extreme tension, as it is in this case, with possible stresses of at least 113 MPa occurring in the cable. When a cable snaps its behavior is unpredictable and could potentially cause severe injury to nearby operators. Injury due to cable failure is expressed by

$$I_{cable} = \rho_2 S_2 (1 - \hat{SF}_{cable}) \tag{24}$$

where

$$SF_{cable} = \frac{S_{ut}}{\sigma_{max}} \tag{25}$$

$$S_2 = 3 \tag{26}$$

Spoke end cap exposure: The original drill design had a plate welded to the end of the spoke, near the handle that operators would grab to spin the drill wheel, see Fig. 3a. Later, this plate was removed for manufacturing simplicity, but it leaves the area vulnerable to injury as a finger may get caught in the end of the spoke, see Fig. 3b. The potential for injury in this location is expressed as

$$I_{spoke} = \rho_3 S_3 E_p \tag{27}$$

where

$$E_p = \begin{cases} 1, & \textit{end plate cover absent} \\ 0, & \textit{end plate cover present} \end{cases} \tag{28}$$

$$S_3 = 2 \tag{29}$$

E_p is simply a binary value to identify if the end plate is present or not. If it is, then the potential for injury in that location is 0. If there is no plate then the potential for an operator to get a finger caught in the spoke is 1 times the probability (ρ_3) of an injury occurring.

Force Exertion: The force required to spin the wheel is dependent on the diameter of the wheel. Principles of mechanical design tells us that as the diameter of the wheel increases the

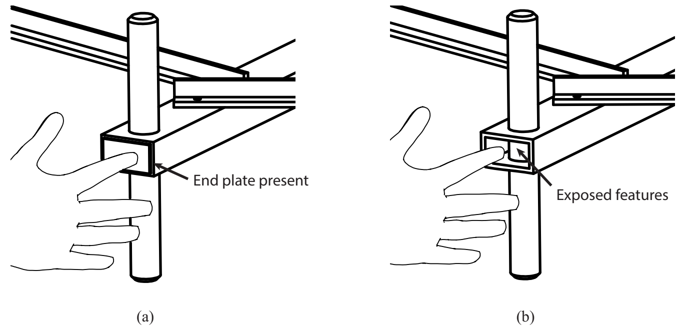

FIGURE 3. SPOKE AND HANDLE DESIGN; (A) SHOWS THE DESIGN WITH THE END CAP ON THE SPOKE WHILE (B) SHOWS THE EXPOSED FEATURES WITHOUT THE END CAP. THIS EXPOSED REGION POSES A POTENTIAL INJURY RISK FOR FINGERS.

force required to produce the same amount of torque decreases. As the wheel diameter shrinks, the operators will have to exert a higher force on the wheel to maintain the required torque on the drill bit. A higher force will result in higher risk of injury which can be expressed as

$$I_{force} = \rho_4 S_4 F_{op} \tag{30}$$

where

$$F_{op} = \frac{2T}{d_w n_{op}} \tag{31}$$

$$S_4 = 1 \tag{32}$$

The potential for injury is the aggregate score of each of the individual injury models. Each equation is normalized and aggregated into the following equation

$$I = \frac{\hat{I}_{stop} + \hat{I}_{cable} + \hat{I}_{spoke} + \hat{I}_{force}}{4} \tag{33}$$

Probabilities: WHOlives.org have no reported injuries due to drill operation, however, it could happen at anytime. The number of potential injury causing events were calculated and used to back calculate the probability for each injury case. This has led to probabilities that are extremely low, which is plausible since no injuries have been recorded in 5 years.

2.2.7 Possible market penetration

To date, the current village drill has produced over 1000 boreholes. 50% of those boreholes have been 42 meters deep or less. The Village Drill has capabilities to reach a depth of up to 73 meters. A square root regression was used to relate the length of the drill string to the fraction of Villages the drill will be able to serve. The relationship for market penetration can be written as

$$M_p = C_1 \sqrt{d_l - C_2} + C_3 \tag{34}$$

where d_l is the drill string length and C_1, C_2,and C_3 are constants found through the regression. These constants are 0.00284, 42,000, and 0.5, respectively. A square root regression was used for this relationship because it would result in a decreasing rate of increase for market penetration as the drill depth capabilities increase.

2.3 Aggregate parameters

In order to use the relationships found in the previous section we need to aggregate the equations into one measure for each category of sustainability.

2.3.1 Aggregate measure of economic sustainability

Economic sustainability will be represented by revenue. Using Eqs. 1 and 4 we have the following aggregated equation

$$S_{\text{eco}} = P - C_{\text{tot}} \tag{35}$$

2.3.2 Aggregate measure of environmental sustainability

Environmental sustainability is represented as the sum of the drill's emissions throughout its life-cycle. Therefore, using Eqs. 6, 7, and 8, environmental sustainability can be represented by the following equation

$$S_{\text{env}} = \varepsilon_{mfg} + \varepsilon_{shp} + \varepsilon_{\infty} \tag{36}$$

2.3.3 Aggregate measure of social sustainability

We use a weighted average to combine Eqs 10, 20, 33, and 34 into a single measure. Each equation is first normalized and then aggregated as shown.

$$S_{\text{soc}} = \frac{w_1 \hat{N}_{ppl} + w_2 \hat{N}_{jobs} + w_3 (1 - \hat{I}) + w_4 M_p}{4} \tag{37}$$

Mattson et al. [1] do not give a new method for aggregating these relationships, but instead point to alternate resources [22]. In the case of the Village Drill, economic and environmental issues have common units of measure (\$, $lbs - CO_2$), therefore combining them was a simple task. The same cannot be said

TABLE 2. THESE 8 CONSTRAINT EQUATIONS ARE USED TO FILTER OUT INFEASIBLE DESIGNS IN THE MONTE CARLO SIMULATION.

Constraint Equations	Description
$\sigma_i < S_y * S_f$	Ensures the Von Mises stress in each steel member stays below its yield strength. S_y = 250 MPa, S_f (safety factor) = 1.5
$l_{spk} < (l_1 - x_{dis}) * cos(\theta) - 200)$	Ensures the wheel assembly will remain at least 200 mm away from the main uprights.
$l_4 > (l_1 * cos(\theta) + 108$	Ensures the base extends at least 108 mm beyond the end of the cantilever
$\theta_{twist} < 360°$	Ensures the total torsional twist in the drill string at full length is less that one full rotation.
$l_{pipe} + 200 < l_3 * 0.3 + (l_1 - x_{dis}) * sin(\theta)$	Ensures that the kelly bar can be raised above drill wheel for additional pipe assembly
$l_{pipe} < l_2$	Ensures that a single length of drill pipe can fit under the wheel support weldment for assembly
$u_1 < 50mm$	Ensures the total deflection of the cantilever is less than 50 mm.
$p_{net} < 0$	Ensures net profit is greater than 0.

for issues regarding social sustainability. This makes weighting these relationships difficult and subjective in many cases. For example, one stakeholder may feel that it is most important to reduce injury as much as possible, even if that means radically decreasing the amount of water provided. This person would then weight 'injury reduction' higher than 'water provided'. Varying opinions on the proper weighting may exist even within a single design team. The problem of weighting social impact issues is still up for much debate and we do not seek to solve it here. Suffice it to say that much work must be done to develop a method for objectively weighting social impacts. Here we simply allow each issue to have an equal weight of 1 within the aggregation.

2.4 Find sustainability space

Using the equations from the previous section we can evaluate the sustainability of any given set of drill parameters. The output values for these three aggregated equations (Eqns. 35, 36, 37) represent the sustainability score for each of their respective categories. The problem formulation can be expressed as:

$$\begin{aligned} \underset{x}{\text{maximize}} \quad & S_{\text{eco}}, S_{\text{env}}, S_{\text{soc}} \\ \text{subject to} \quad & x_{i,min} \leq x_i \leq x_{i,max},\ i = 1, \ldots, n \\ & c_{j,min} \leq c_j \leq c_{j,max},\ j = 1, \ldots, m \end{aligned} \tag{38}$$

where x represents the design parameters and c represents the constraints. For this model we have 22 design parameters, found in Table 1, and 8 constraints, found in Table 2.

A Monte Carlo simulation – commonly known as the brute force method – took one million randomly generated design alternatives and evaluated them based on the equations found in section 2.4. Each design was also evaluated for defects (ie. inability to assemble, beam member failure, etc.) and infeasible designs were removed from the dataset. Additionally, the design space was normalized so that each solution could be plotted on a

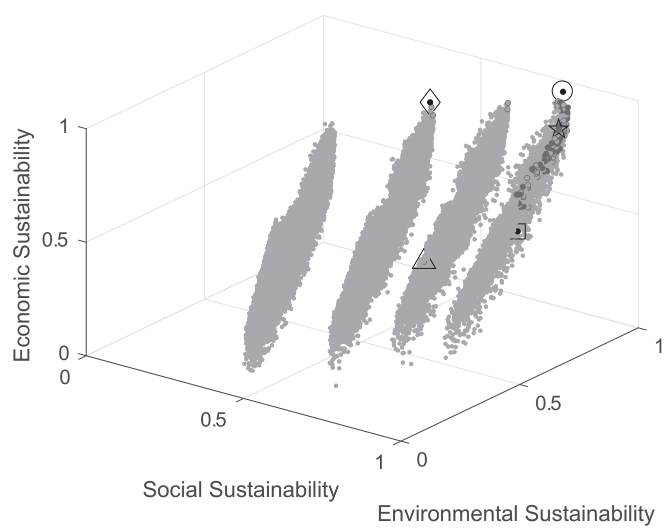

FIGURE 4. SUSTAINABILITY DESIGN SPACE FOR THE VILLAGE DRILL. THE SOLUTIONS HIGHLIGHTED WITH A SQUARE AND DIAMOND ARE THE DRILL DESIGNS THAT RECEIVED THE BEST SOCIAL AND ECONOMIC SCORE, RESPECTIVELY. THE SOLUTION HIGHLIGHTED WITH A TRIANGLE IS THE CURRENT VILLAGE DRILL DESIGN AND IS SHOWN HERE FOR THE PURPOSE OF COMPARISON, THE SOLUTION WITH A CIRCLE AROUND IT IS USED FOR DISCUSSION. NON-DOMINATED SOLUTIONS ARE A LIGHTER GRAY WHILE PARETO SOLUTIONS ARE REPRESENTED BY A DARKER POINT.

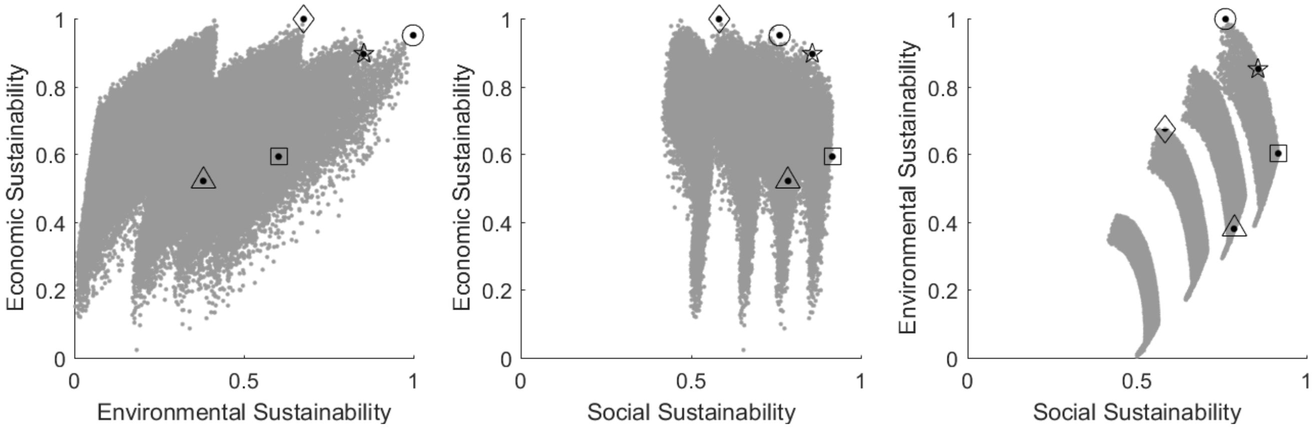

FIGURE 5. SUSTAINABILITY DESIGN SPACE FOR THE VILLAGE DRILL SHOWN HERE IN TWO DIMENSIONAL SNAPSHOTS. THE SOLUTIONS HIGHLIGHTED WITH A SQUARE AND DIAMOND ARE THE DRILL DESIGNS THAT RECEIVED THE BEST SOCIAL AND ECONOMIC SCORE, RESPECTIVELY. THE SOLUTION HIGHLIGHTED WITH THE TRIANGLE IS THE CURRENT VILLAGE DRILL DESIGN SHOWN HERE FOR THE PURPOSE OF COMPARISON, WHILE THE SOLUTION HIGHLIGHTED WITH A CIRCLE IS USED FOR DISCUSSION. EACH HIGHLIGHTED DESIGN IS SHOWN IN FIG. 6

scale of 0 (worst) to 1 (best) in each category of sustainability.

Fig. 4 shows the sustainable design space for the Village Drill. Each data point represents a possible design alternative while the darker points represent non-dominated solutions (Pareto points). We have provided two dimensional snapshots, found in Fig. 5, to provide a better visualization of the tradeoffs between categories. For further reference, Fig. 6 provides an updated model of the Village Drill for each highlighted solution found in the plots in Figs. 4 and 5.

3 Model Results

Fig. 5 shows two dimensional snapshots of the sustainable design space for the Village Drill. The point with a triangle around it represents the current Village Drill design. This figure also shows that, according to our model, the current Village Drill has potential to improve in each of the three categories of sustainability.

The value of this model is found in discovering the tradeoffs between each pillar of sustainability, and the data can be a tremendous benefit to decision makers and designers of the Village Drill. For example, Fig. 5 shows three points that are the best performing design in regard to one specific category. These points are represented by a diamond, representing the best economic point, circle (environmental) and square (social). If WHOlives.org desired to focus on a drill that maximizes economic profits then we recommend choosing the design with a diamond around it. However, this results in significant tradeoffs with the other two sustainability categories, as shown in the far-right image of Fig. 5. This design performs poorly in regards to social and environmental sustainability. As WHOlives.org is a nonprofit organization they may be inclined to select the highest performing design for social sustainability, shown with a box surrounding it. Similar to the best economic design, choosing this design also has its tradeoffs.

The design identified as "recommended" (shown in Fig. 5 with a circle) performs well in each of the three categories. When compared to the best economic point, this design makes improvements in social sustainability while allowing a minimal reduction in economic sustainability. We see a similar situation for the environmental impact of this design. While it is not the optimal choice for any of the three pillars of sustainability alone, the tradeoff in each is relatively small. Decision makers may be inclined to choose this design over others because it performs well in each of the three categories despite not being the best option in any of them. The key insight gained by this design is that the current drill can improve in each category, with significant improvements being realized in economic and environmental sustainability.

Identifying these tradeoff conditions offer a development team an intuitive way to view the sustainable design space for the drill. In turn, they can then use the information to choose a design that best represents the values of the company and society.

Table 3 shows each of the five identified designs and several key dimensions for each. It is interesting to note that the cross sectional area decreased for most of the main beam members while their lengths increased. It is important to note that these designs were not found using any optimization algorithm. This means that the drill design we have identified as the best economic option is only the best in our one million piece data set.

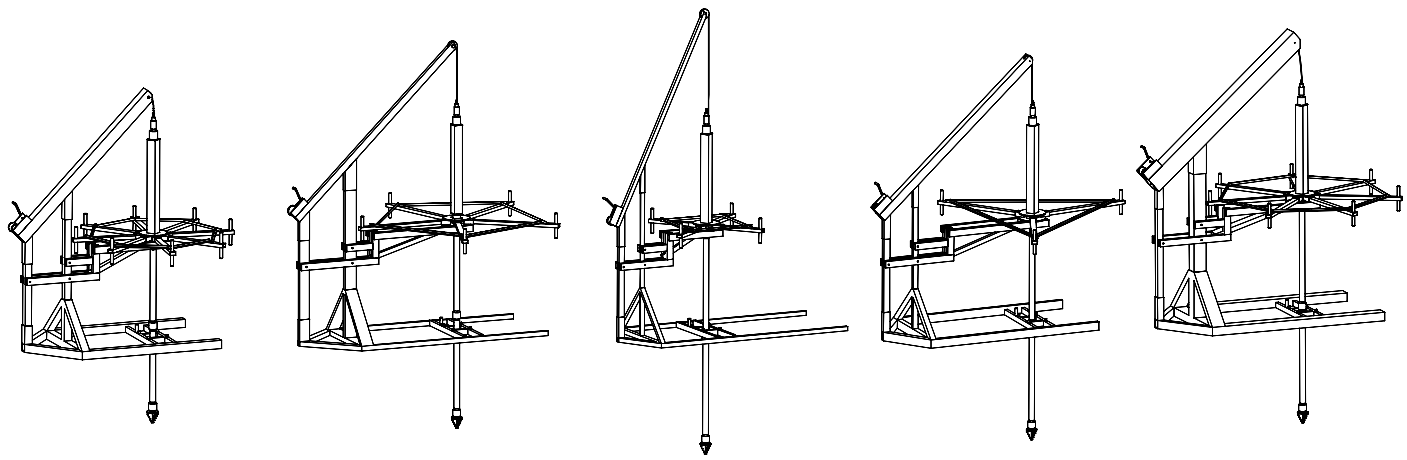

FIGURE 6. UPDATED DRILL DESIGNS FOR EACH SOLUTION IDENTIFIED IN FIG. 5.

TABLE 3. DIMENSION COMPARISONS ARE SHOWN FOR THE FIVE HIGHLIGHTED DESIGNS IN FIG. 5. THE SHAPES NEXT TO EACH DESIGN NAME CORRESPONDS WITH THE SHAPES ON THE TWO DESIGN SPACE PLOTS.

Design Comparison					
Dimensions (units)	**Original (△)**	**Recommended (⋆)**	**Economic (⋄)**	**Environment (○)**	**Social (□)**
L, Cantilever Beam (*mm*)	2134	2539.4	2678	2539.4	2415.7
A, Cantilever Beam (cross section, mm^2)	2856	4224	1101.24	4224	10553.44
L, Short Vert. Support (*mm*)	1219	1413.8	1453.3	1413.8	1597.2
A, Short Vert. Support (cross section, mm^2)	1656	727.04	424	727.04	804
L, Long Vertical Support (*mm*)	1681.4	1753.4	2061.9	1753.4	1979.8
A, Long Vert. Support (cross section, mm^2)	1656	276	224	276	2900
L, Base Support (*mm*)	1626	2113.7	2413	2113.7	2147
A, Base Support (cross section, mm^2)	2016	804	344	804	4400
θ, Cantilever Beam (*deg*)	45	42.3	64.8	42.3	41.2
L, Drill Pipe (*mm*)	900	1194.8	1199	1194.8	1193
L, Spokes (*mm*)	811	1138.5	632.6	1138.5	1067.1
End Cap Present	Yes	Yes	No	No	Yes

It is very likely that there is a better drill design for economic sustainability that our data set did not include. For example, representatives of WHOlives.org mentioned an economic benefit to having the cross sectional dimensions (h, w, t) for all the beams in the drill be the same. This benefit occurs because it simplifies purchasing as well as manufacturing. However, of the one million random drill designs generated, there were no designs that had all four beams with the same cross sectional dimensions and only 30 designs had matches for three of the beams. It is likely that an economically focused design similar to the best identified here, but with beams that have the same cross sectional dimensions, will perform better in economic sustainability. Table 4 summarizes the improvements (and losses) realized by each new drill design highlighted in Fig. 6.

TABLE 4. USING THE ORIGINAL DESIGN AS A BASELINE, THIS TABLE PRESENTS THE IMPROVEMENTS (AND LOSSES) EACH NEW DRILL DESIGN ACHIEVES FOR EACH ASPECT OF SUSTAINABILITY.

Sustainability Improvement from Original Design				
Sus. Issue	**Recom. (⋆)**	**Eco. (◇)**	**Env. (○)**	**Soc. (□)**
Economic	+72.1%	+91.8%	+82.6	+13.8%
Environment	+124.4%	+78.0%	+163.1	+58.5%
Social	+9.1%	-25.9%	-3.2	+16.6%

4 Concluding Remarks

This paper combined two contributions by Mattson et al. [1, 2] to create the sustainability space for the Village Drill. With the assistance of WHOlives.org, relationships were found between design parameters and the sustainability issues most important to the organization and society. These relationships provided a three-dimensional design space for the Village Drill where tradeoffs could be easily visualized and evaluated.

From the design space, new drill parameters were identified that could increase its sustainability in each of the three pillars of sustainability. Alternate design parameters were identified that could maximize the Village Drill's impact in a single category of sustainability while ignoring the other two.

These efforts do not come without their limitations. Weighting and aggregation may be the greatest limitation found within this model. The social element of sustainability is still young in its development and as such there are no accepted methods for combining and assigning weights for these issues. Future work is recommended to run an optimization routine on the given model to find designs that are truly optimal.

ACKNOWLEDGMENT

This material is based upon work supported by the National Science Foundation under Grant No. CMMI-1632740. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

The authors also wish to acknowledge and thank WHOlives.org for their collaboration and data regarding the Village Drill.

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