Village Drill: A Case Study in Engineering for Global Development With Five Years of Data Post Market-Introduction

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This paper presents a case study in engineering for global development. It introduces the Village Drill, which is an engineered product that has—5 years after its introduction to the market—enabled hundreds of thousands of people across 15 countries and three continents to have access to clean water. The Village Drill creates a 15 cm (6 in) borehole as deep as 76 m (250 ft) to reach groundwater suitable for drinking. The case study presents facts for the actual development and sustaining and are unaltered for the purpose of publication. This approach provides the reader with a realistic view of the development time, testing conditions, fundraising, and the work needed to sustain the drill through 5 years of sales and distribution. The purpose of the case study is to provide sufficient and frank data about a real project so as to promote discussion, critique, and other evaluations that will lead to new developments that inspire and inform successful engineering for global development. As part of the case, the paper describes six fundamental items: the product, the customer, the impact, the manufacturing, the delivery, and the revenue model of the drill. [DOI: 10.1115/1.4036304]

Keywords: engineering for global development, design for the developing world, poverty alleviation, clean water, Village Drill

1 Engineering for Global Development and the Need for Case Studies

Engineering for global development is an interdisciplinary practice that aims to improve the quality of life of underserved communities worldwide through the design and delivery of technology-based solutions [1]. Participation in engineering for global development is often motivated by societal altruism, a desire to tap into new global markets, and/or interest in advancing technology to extreme limits [2].

While a growing number of individuals are motivated to participate in engineering for global development, it has proven to be difficult to do it successfully and sustainably [3,4]. The difficulty is not yet fully understood, but is influenced by large physical distances and cultural differences between engineers and end-users, stakeholder imbalance [5], and the realities of high experimental costs in highly uncertain environments [6].

Some engineering work is beginning to appear in the literature that can guide the general process of engineering for global development [7–11], but it is realistic to acknowledge that the current state of knowledge is in its infancy. One specific thing missing from the literature is case studies with years of data showing how engineering efforts eventually lead to positive impact. Also missing are descriptions of what happens between initial in-field product development experiments and scaling up to reach large numbers of people. Frank and unembellished case studies of this nature have the potential to inspire and inform successful engineering for global development.

The purpose of this paper is to present the Village Drill as a case study. It presents facts for the actual development and sustaining and is unaltered for the purpose of publication. We believe that this approach will provide the reader with a realistic view of the development time, testing conditions, fundraising and cash-flow, sustaining, sales, and distribution for a technical product engineered for a developing world setting.

2 The Village Drill Case Study

The Village Drill is a human powered machine that creates boreholes for water wells. Figure 1 conveys the basic drill functionality. As shown, the drill is operated by spinning the input wheel, while lowering the drill string in a controlled way using the hand-operated winch. The drill string is an assembled length of 6 cm (2.5 in) diameter drill pipes and a 15 cm (6 in) diameter bit. The drill is designed to reach water up to 76 m (250 ft) below the surface. Chips from the drilling are removed as a mixture of water and commercial-grade bentinite is pumped down the drill pipe through the bit. Chips are brought back to the surface by the mixture through the annulus around the pipe. At the surface, the chips are removed from the fluid mixture in a small settling pond and the fluid is repumped into the drill string.

The Village Drill belongs to WHOlives.org—a nonprofit organization that commissioned Brigham Young University (BYU) to design and test the Village Drill. The key impact measures for the drill, representing its full 5-year history, are presented in Table 1. Note that the data in this table do not account for uncertainty and are therefore deterministic. The deterministic analysis is described in Sec. 2.5 and the effects of uncertainty are accounted for in Sec. 2.9.

After providing a brief introduction to the case study (Sec. 2.1) and its timeline (Sec. 2.2), six fundamental parts of the project are then discussed: product, customer, impact, manufacturing, delivery, and revenue model. These six parts were chosen to be consistent with the discussions laid out by Wood and Mattson [4] about avoiding failure in a developing world setting.

2.1 Case Study Introduction. Providing access to clean water is one of the world's greatest engineering challenges. It is one of the 14 grand challenges of the 21st century as defined by the National Academy of Engineering [12]. Even so, this challenge can be easily overlooked since most of the world's engineers have continuous uninterrupted access to clean water, and are therefore far removed from this challenge and its effects. The water disparity between developed and developing parts of the world is significant. For example, most estimates put water consumption in the U.S. at 303–379 L (80–100 gal) per day per person, while water for domestic use in Rwanda is 9.11 L (2.41 gal) per person per day. To put this into perspective, the amount of daily water available per person in Rwanda is consumed in 73 s using a low flow environmental protection agency certified WaterSense shower head [13].

This case study is focused on accessing drinkable ground water. There are three broad challenges associated with accessing this water. They are: (i) knowing *where* to drill a borehole that will access extractable ground water, (ii) knowing *how* to cost-effectively drill a borehole to reach the water, and (iii) knowing

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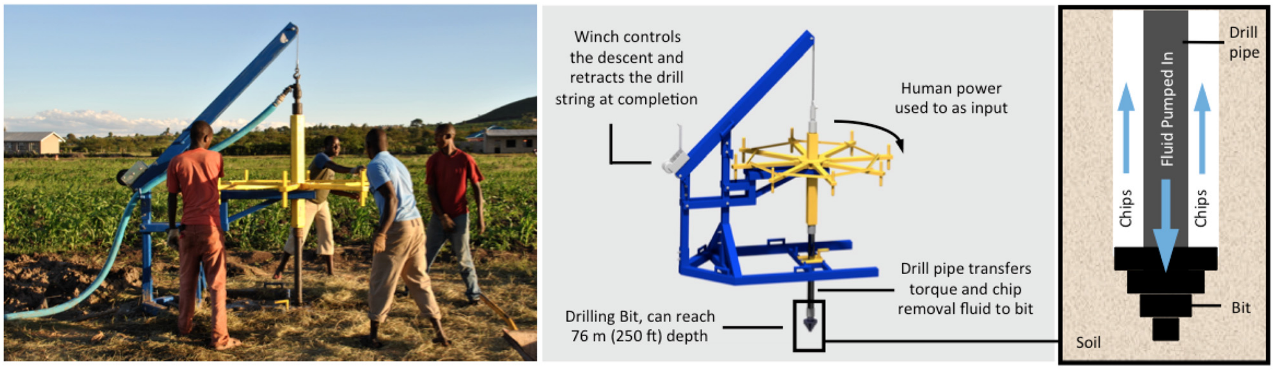

Fig. 1 Village Drill: (*a*) in use in Tanzania, (*b*) description of basic function, and (*c*) detail of drilling bit and chip removal

Table 1 Village drill measures after 5 years ($n_t = 65$)

Productivity measures	
Drills produced in total (n_d)	41
Drills in service (n_{d_s}) during time period 65[a] ($n_t = 65$)	34
Productive boreholes drilled in total (n_{b_t})	761
Productive boreholes drilled (n_{b_p}) during $n_t = 65$	31
Primary impact measures	
Wells in service (n_{w_s}) during $n_t = 65$	453
People being served (drinking) (n_{pops}) during $n_t = 65$	188,176
Unique people served (drinking) in total ($n_{\text{pops}_{\text{max}}}$)	316,281
People-months of water provided in total (n_{pmws})	4,129,945
Secondary impact measures	
Countries using the Village Drill during $n_t = 65$	15
Acres irrigated (n_{as}) during $n_t = 65$	109
Acres-months of irrigation provided in total (n_{amws})	2385
People employed (on drills) (n_{pope}) during $n_t = 65$	238
Months of employment created (on drills) (n_{pme}) in total	5838
Total income through fund raising (USD)	$448,375
Total income through drill invoices (USD)	$658,500

[a]Time period 65 is the last month evaluated before publication.

how to prepare and maintain the system that goes into the borehole to extract the water. While all of these challenges were faced and dealt with during the history of the Village Drill, this case study focuses specifically on the second item—how to cost-effectively drill a borehole.

There are a number of ways to produce boreholes to access drinkable ground water. The most common is to use a professional scale well-drilling rig. These systems can drill deep holes (hundreds of meters) through rock relatively quickly. Creating a borehole with a well-drilling rig in Africa can cost between $15,000 and $25,000 USD. Because of their large size, these drilling rigs cannot access most villages or cannot drill a hole in a desirable location such as in the center of a small community. These drawbacks make well-drilling rigs financially and physically inaccessible to a large number of people.

When drilling rigs are inaccessible, two alternative approaches are often pursued: hand auguring and sludging. Hardware for these approaches are inexpensive, but are slow and laborious to use, are restricted to relatively soft soils, and are limited in depth-of-cut. The simplest forms are limited to creating holes approximately 10 m deep. The most advanced forms can reach depths of 100 m. The inexpensive nature of these devices has improved access to ground water for many people. Both of these alternative methods are suitable in loose soils and with adaptation can be used in more diverse soil types. However, neither is well-suited for medium to hard rocks formations. The Village Drill was created to compete in between the well-drilling rig and hand auguring/sludging space.

The Village Drill case study has five fundamental components at its foundation. The articulation of these components is consistent with the accepted case study research methodology [14]. For this case study, they are:

(1) *The case study's question*: What impact has the Village Drill had on water-poor individuals?
(2) *The case study's propositions*: The Village Drill has served people in need of drinking and irrigation water. The Village Drill has given employment to Village Drill operators.
(3) *The case study's subject of analysis*: The Village Drill.
(4) *The logic linking case study's data to the proposition*: The Village Drill produces boreholes. Not all boreholes successfully lead to water. Those that do are fitted with a pump and become a functioning well. Water-poor individuals access clean water via the well. Not all wells get maintained, some fall out of service. Some individuals who gained access to water have lost it when wells are not serviced. Each borehole drilled employs a set of drill operators.
(5) *The criteria for evaluation*: In any impact analysis, such as the one offered in this paper, it would be easy to intentionally or unintentionally overstate the impact achieved. To guard against this, we use two layers of protection in this paper. Both are described in more detail below: the first is that we have chosen to use the most conservative parameter values that we have evidence for in the impact analysis. Second, we have carried out a detailed uncertainty analysis and expressed the impact achieved in terms of confidence intervals greater than 97%.

2.2 Village Drill Timeline. A detailed timeline is provided in Fig. 2. The left half of the figure shows product development milestones, while the right half shows delivery and drilling milestones. Notice that the solid black circles represent drills that entered service, and that the gray arrow boxes represent field trips. For convenience of seeing the data in one figure, the data shown on the extreme right side of the image indicate borehole depth to scale and is unrelated to time—except for the parenthetical note of when those depths were achieved.

Several valuable pieces of information are found in the figure. For example, a large portion of the product development time spent by BYU (5–6 months) was in developing a system concept that would meet WHOlives.org's and end-users' needs. Once that system concept was chosen and its parts were tested, the detailed engineering of the Village Drill was carried out relatively quickly (2–3 weeks).

Another observation from the data presented in the figure is that WHOlives.org focused for approximately 2 years on just two countries (Kenya and Tanzania) before expanding out to 13 additional

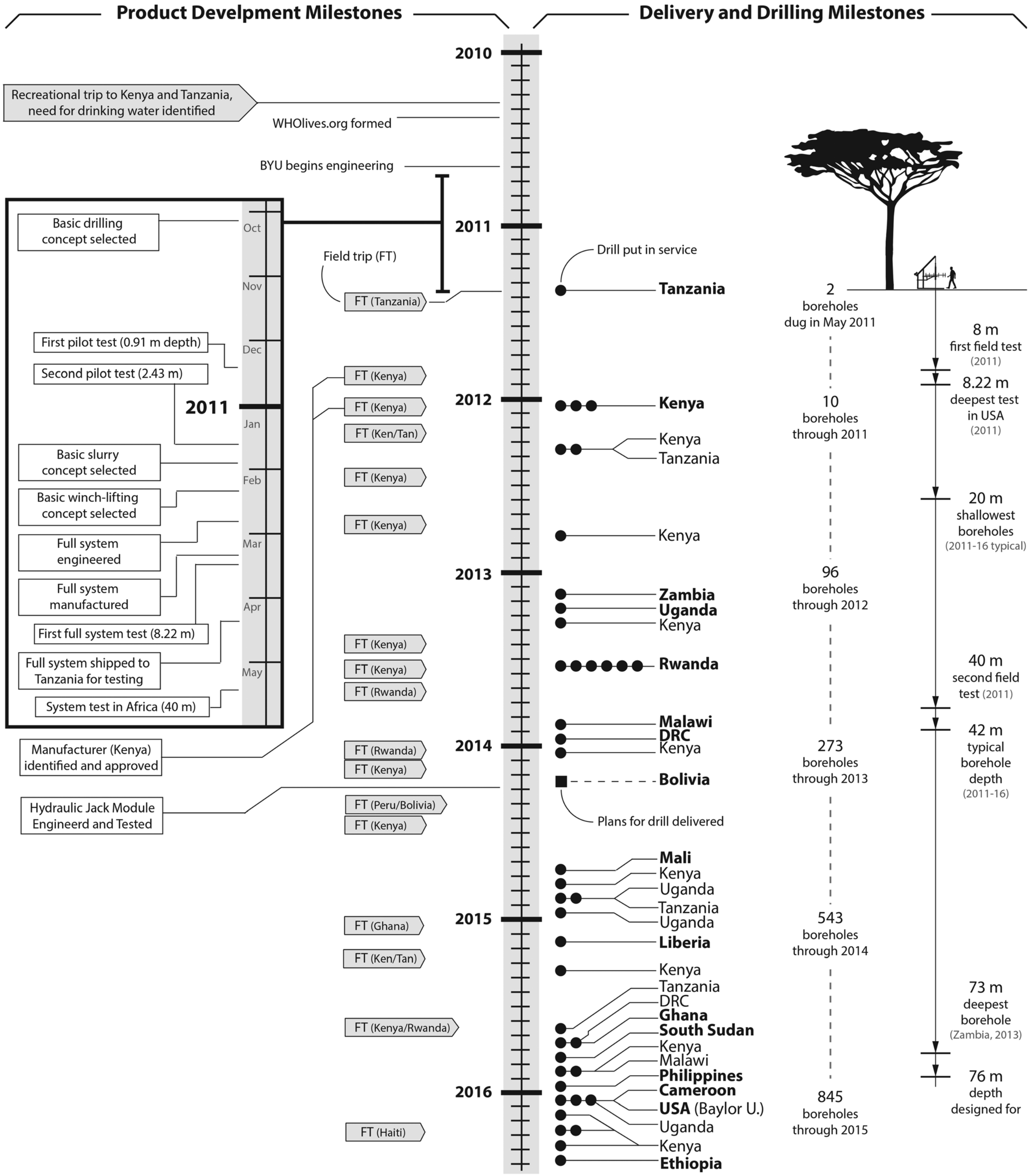

Fig. 2 Timeline for product development and delivery/drilling milestones

countries in the 3 years that followed. It is also worth acknowledging the 17 field trips that were required to carry out the project during the past 5 years. Section 3 of this paper presents more about the data shown in Fig. 2.

2.3 Product. The Village Drill was designed by two of the authors (Mattson and Renouard) together with multiple students (listed in the acknowledgment). The basic system is shown and described in Figs. 1 and 3. The drill was designed to use as much proven well-drilling technology as possible, while being human powered as much as possible. This strategy was chosen to reduce technical risk, and due to the simple nature of the design, reduce cost and complexity—thus making the drill more desirable and accessible, and therefore reduce market risk.

In the early stages of product development, the most important customer needs were identified as follows:

(1) The drill reaches potable water beyond 30 m (100 ft).
(2) The drill cuts through rock.
(3) The drill uses existing drill bits.
(4) The drill seals borehole sides to prevent cave-in.
(5) The drill removes cuttings from the borehole.
(6) The drill works at an efficient speed.

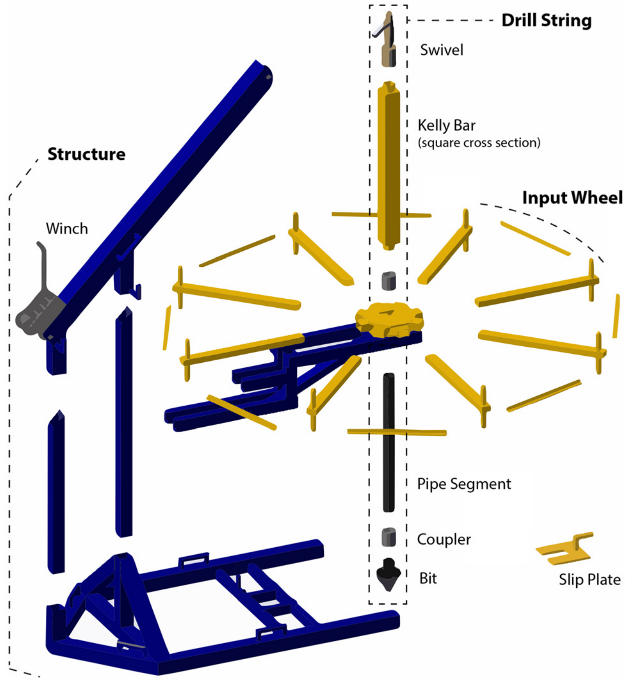

Fig. 3 The major subsystems and parts of the Village Drill. The structure divides into five parts; the base, the boom, the wheel support, and two vertically oriented beams to give the boom height. The input wheel has a center hub (welded) with eight spokes that extend from it and are secured by eight cross members. The drill string includes the swivel, Kelly bar, and many short (meter-long) pipe segments and couplers that are added to the drill string as the borehole deepens. The Village Drill disassembles into the pieces shown for transport to and from the job site.

(7) The drill uses only human power to operate.
(8) The drill is portable.
(9) The drill is comfortable to operate.

These were translated (using the concepts of quality function deployment [15]) into multiple performance measures including borehole depth, downward drilling force, applied torque to drill pipe, weight of heaviest subassembly, etc.

Designed to meet these needs, the Village Drill fills a unique spot in the market; for relatively shallow borehole depths (<76 m), the drill mimics a large-scale drilling rig at much lower financial cost and requires significantly less technical knowledge to operate.

The Village Drill has four major subsystems, three of which are shown in Fig. 3: the structure, the drill string, and the input wheel. The fourth subsystem is the pumping system and is not shown. The Village Drill is designed to come apart into the pieces shown in Fig. 3, and be transported to the job site in a small pick-up truck, cart, or by hand for up to 1 km distance.

The basic concept/configuration of the Village Drill was chosen for specific reasons: (i) The wheel was oriented horizontally at an ergonomic height to make the best use of biomechanics. The operators remain stationary, while using their upper body to push the wheel in a clockwise fashion. The wheel acts as a large flywheel that keeps the wheel spinning with minimal strain on the body. The winch plays an essential role in the functionality of the Village Drill; it prevents the drill string from wedging itself into the soil. When wedged into soft soils, the drill string cannot be turned sustainably by human power. The winch also retracts the drill pipe once ground water is reached. The wheel support attaches to the vertical part of the structure to leave as much room around and under the wheel as possible to improve safety of operation and ease of adding pipe segments to the drill string. The wheel, wheel support, Kelly bar, and swivel are designed to be easily removed from the structure once water is reached. The structure is then used as a hoist to remove the drill string, two pipe segments at a time. The design of the pipe couplers and the drill base are such that a plate (shown as slip plate in Fig. 3) can be slipped around the drill pipe and under the coupler to hold the weight of the drill string while the pipes above it are removed and is no longer supported by the winch. The slip plate rests on the cross members shown between the legs of the base. These specific innovative features were chosen to rectify problems identified in the pilot tests performed in the U.S. (in late 2010 and early 2011, as shown in Fig. 2).

Two other parts of the concept/configuration are essential to the Village Drill and are strategically chosen from existing well-drilling technology. The first is the interface between the input wheel and the drill string. The technology used is termed a *Kelly bar*. The Kelly bar slips through a square opening in the input wheel as shown in Fig. 3. This allows the wheel to apply a torque to the Kelly bar, while simultaneously allowing the bar to descend into the borehole as the hole deepens. The other parts of the drill string are also chosen from existing technology: the drill bit, the drill pipe (though shortened to 1 m sections), and the swivel.

The second major subsystem chosen from existing technology is the pumping system. Existing rig-based drills pump a water/bentinite mixture through the drill pipe as shown in Fig. 1(*c*). The purpose of this mixture is to remove the cutting chips and seal the borehole. The basic concept for the Village Drill (in this regard) is equivalent to that of existing drilling technology. For the Village Drill, a small petrol-powered slurry pump is used to pump the water/bentinite mixture down the drill pipe while it is being spun by the operators.

After the initial testing of the Village Drill in Tanzania (2011), and making minor changes, relatively few modifications have been made to the Village Drill. Three system modules, however, were added over time. In 2011, weight collars were designed and added to the Village Drill system. These collars slip over the first drill pipe (closest to bit). The bit keeps the collar from slipping off. The collar provides an additional downward force for drilling through rock. In 2013, additional drill bits were added to the Village Drill system. Originally the system only included a drag bit. Later it included both a drag bit and a tri-cone bit. In 2013, WHOlives.org engaged BYU to design a module to apply more downward pressure to drill through rock. The module attaches to the Village Drill boom and uses a hand-operated hydraulic jack to apply a large downward force, while the drill itself is secured with earth ties.

2.4 Customer. When the Village Drill was being developed, it was intended to be used as a microbuisness, where a local person would rent or buy the drill and then increase their income by drilling wells for other people. This is still one part of the long term goal, but purchasing a Village Drill is a massive investment resulting in all of the manufactured drills having been purchased by either nongovernmental organizations (NGOs) or wealthy individuals in the developed world who donated them for use in developing communities. The primary customers for the Village Drill are NGOs. In the initial years of distribution, these NGOs were based primarily in Africa. In the subsequent years, however, WHOlives.org has started to serve NGOs in South America, and Asia as well. Customers pay $18,000 USD for a Village Drill and training. This includes bits, drill pipe, couplers, and everything needed to drill.

WHOlives.org owns and operates four of the 41 drills that have been produced. Using these four drills, WHOlives.org drills boreholes for those who are not in the market for a Village Drill but are in the market for a borehole. These borehole customers range from individuals, to schools, to villages, and to farmers. These customers pay approximately $4000 USD for a productive borehole with a hand pump installed.

2.5 Impact. Five years after introducing the drill to the market, WHOlives.org and BYU worked closely together to develop a meaningful set of impact models for the Village Drill. These models were derived and refined using data and experience from WHOlives.org's founder, its African business development leader and its African well-drilling teams. The models presented here are centered on the measures deemed most important to WHOlives.org. We present them as part of the case study so as to make it clear how each impact measure was calculated, what parameters were involved, and how they were chosen. This coupled with the raw data provided in the Appendix allows others to use this case study as the basis for additional studies.

2.5.1 Productivity Measures. In this section, we describe productivity measures used to judge WHOlives.org's efforts to use the Village Drill to create productive boreholes. Note that the smallest time increment used to make these judgements is 1 month, and that the numbers labeled *total* represent the total sum over the full history of the drill.

The total number of drills produced (n_d) is tracked via drill invoices; the total is listed in Table 1. To create realistic measures, we account for the fact that some drills are sitting idle (functional, though not in service) or have been retired from service. Therefore, the number of drills in service for any given month is evaluated as

$$n_{d_s} = n_d - n_{d_{os}} - n_{d_r} \tag{1}$$

The value $n_{d_{os}}$ varies month-to-month and is relatively well-known for all time periods, and the number of retired drills (n_{d_r}) is known to be 0. Section 2.9 includes an analysis to account for the uncertainty in the model's input parameters, including $n_{d_{os}}$.

A productive borehole accesses useable water. Only a fraction of the boreholes created are productive (hit water). The number of productive boreholes drilled (n_{b_p}) for any time period is calculated as

$$n_{b_p} = n_{d_s} * n_{\text{bpm}} * f_{b_p} \tag{2}$$

where n_{bpm} is the average number of boreholes drilled per Village Drill per month and f_{b_p} is the fraction of boreholes that are productive. For this paper, these values are estimated for all drills as 1.25 and 0.73, respectively. These values are chosen by examining the work of WHOlives.org's drilling team and then extending to all other NGO drilling teams not operated by WHOlives.org. The total number of productive boreholes created, n_{b_t}, is simply the sum of n_{b_p} over all time periods.

2.5.2 Primary Impact Measures. While the productivity measures are directly related to the Village Drill, they are a step removed from the intended impact, which is centered on people—not drills. In this section, we present the primary impact measures used to judge the value of the Village Drill.

We assume that each productive borehole is cased and a hand pump is installed to create a well. Hand pumps, however, require servicing to remain functional and only a fraction of the pumps installed will receive their first service. As a result, the number of wells in service increases when productive boreholes are created and decreases when wells do not receive their first service. During the initial part of the project, before reaching the expected life (l_{mbf}) of a pump before its first service, the number of wells in service per month can be estimated as

$$n_{w_s} = \sum_{i=1}^{n_t} n_{b_p i} \quad \text{when} \quad n_t \le 14 \tag{3}$$

where n_t is the number of time periods (months) used in the analysis. For this analysis, $n_t = 65$ and $l_{\text{mbf}} = 10$. The number 14 is chosen for the inequality because the first borehole was drilled 4 months after the first time period of the analysis. The number 14 is simply the summation of those 4 months and the 10 months representing l_{mbf}. After the initial period of the project, the number of wells in service can be estimated as

$$n_{w_s} = \sum_{i=1}^{n_t} n_{b_p i} - \sum_{i=1}^{n_t - l_{\text{mbf}}} n_{b_p i}(1 - p_{\text{fms}}) \quad \text{when} \quad n_t > 14 \tag{4}$$

where p_{fms} is the probability that a pump will receive its first service at or before the pump life expectancy (l_{mbf}) is reached. Unfortunately, the probability of hand pumps being serviced is globally low—potentially as low as 0.15. Nevertheless, in consultation with WHOlives.org's drilling teams and considering the WHOlives.org training and support system, we estimate this probability to be 0.4.

Given the number of wells in service, we can calculate the number of people served each month. It is typical to estimate that a well can serve 1000 people. However, to be as realistic as possible, we consider 1000 people to be an upper limit. Instead, informed by the experiences of WHOlives.org, we categorize wells in service as being used in three different ways: (i) to serve a village (drinking) near its center, (ii) to serve a village (drinking) on the outskirts of the village, and (iii) to serve acreage (irrigation). The fraction of wells serving a village center (f_{hub}) is assumed to be 0.78. The fraction serving the outskirts (f_{rim}) to be 0.16 and the fraction irrigating acreage (f_a) to be 0.06. These fractions were chosen by examining the work of WHOlives.org's drilling team and extending the same fractions to all drilling teams. The number of people served (drinking) per month is estimated as

$$n_{\text{pops}} = n_{w_s}(f_{\text{hub}} * n_{\text{hub}} + f_{\text{rim}} * n_{\text{rim}}) \tag{5}$$

where the estimated number of people served at the village center (n_{hub}) is conservatively chosen as 500, and the number of people served on the outskirts of the village (n_{rim}) is 160 per well.

Given that pumps in service go out-of-service if not maintained, WHOlives.org keeps track of the total number of unique people served (drinking) over all time periods ($n_{\text{pops}_{\max}}$). Comparing this number to those served in the last time period (n_{pops}) lends insight into the number of people once served who are no longer served.

To value the cumulative effect of time, it is meaningful for WHOlives.org to estimate the total number of people (not unique people) who have had access to a well for at least one month. We call this number *people-months of water provided* (n_{pmws}), and calculate it as

$$n_{\text{pmws}} = \sum_{i=1}^{n_t} n_{\text{popsi}} \tag{6}$$

2.5.3 Secondary Impact Measures. This section presents additional, secondary impact measures that are important to WHOlives.org.

The number of acres served (irrigation) per month (n_{as}) is calculated as

$$n_{\text{as}} = n_{w_s} * f_a * n_{\text{apw}} \tag{7}$$

where f_a is the fraction of wells used for irrigating acreage, and n_{apw} is the average number of acres irrigated per well. The latter is set to 4 acres per well as determined by WHOlives.org's director of drilling and installation in Kenya.

Cumulatively, the total number of acre-months of water provided (acres that have received one month of water) is simply the sum of n_{as} over all time periods

$$n_{\text{amws}} = \sum_{i=1}^{n_t} n_{\text{asi}} \tag{8}$$

Another important measure for WHOlives.org is the number of jobs created because of the Village Drill. The number people employed per month operating drills (n_{pope}) is evaluated as

$$n_{\mathrm{pope}} = n_{d_s} * n_{\mathrm{popepd}} \tag{9}$$

where n_{popepd} is the number of people employed per drill per month. The cumulative number of people-months of employment created operating drills is

$$n_{\mathrm{pme}} = \sum_{i=1}^{n_t} n_{\mathrm{popei}} \tag{10}$$

2.5.4 Time Series Evaluations. The productivity and impact measures presented in Eqs. (1)–(10) can be used to track productivity and impact over the past 5 years for the Village Drill. Time series plots are provided in Figs. 4 and 5.

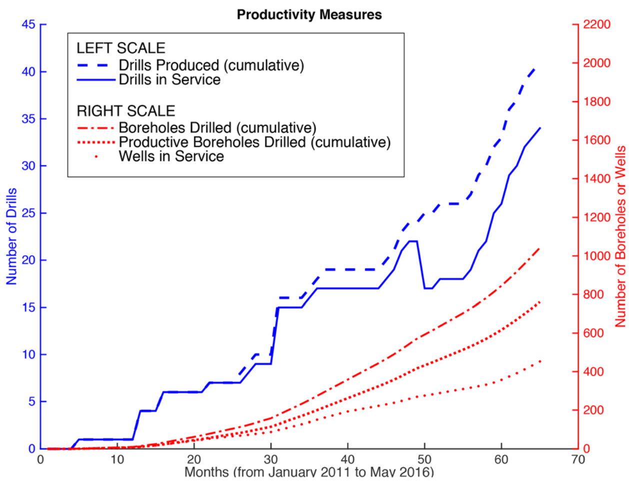

Fig. 4 Time series plot showing productivity measures and wells in service

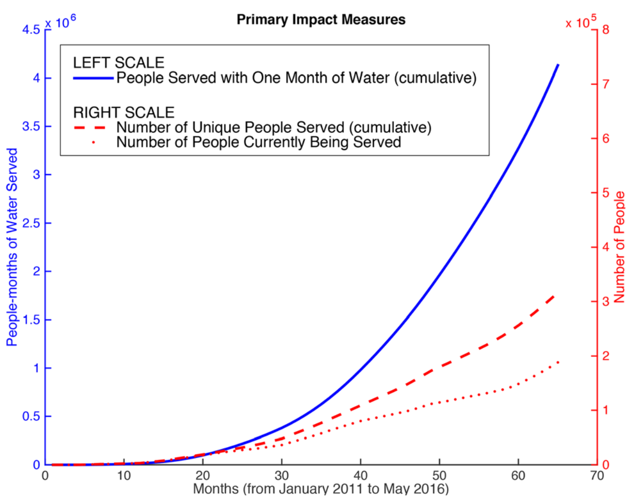

Fig. 5 Time series plot showing the primary impact measures. The total number of people-months of water served is 4,129,945. The number of people who have access to a well (at time period 65 ($n_t = 65$)) with a functioning pump equals 188,176, while the number of people who could have access to water if all pumps were serviced equals 316,281.

2.6 Manufacturing. The first Village Drill was manufactured in the U.S. and shipped to Tanzania. For the next several years, drill frames were manufactured in Kenya and parts including the pulley and the drill bit were shipped from the U.S. In the latter portion of its 5-year history, however, WHOlives.org moved the majority of the manufacturing back to the U.S. and uses the shipping destination to determine the manufacturing location. If the drill will be delivered within 2000 km of the manufacturer in Kenya, then it is made there and shipped via ground transportation. For any other location, the drill is manufactured in the U.S. and shipped.

2.7 Delivery. The Village Drills are delivered in a crate that weighs 1100 kg (2425 lbs) and is 2.3 m (7.5 ft) $\times$ 0.9 m (3 ft) $\times$ 1.2 m (4 ft). When an organization purchases a drill, they also pay for a WHOlives.org worker to travel to their location and train them on the use of the drill. It only takes a few hours to learn how to put the drill together and operate it but the worker usually stays with the group for about 3 weeks and also trains them in drilling basics—how to find water, what to do when the drill gets stuck, casing a borehole, etc. Because drills have started going to countries farther and farther away from where these workers live, WHOlives.org has developed a training manual to send with the drill. This manual mostly consists of pictures that can be understood by speakers of any language.

2.8 Revenue Model. It is essential for people engaged in engineering for global development to understand how the hoped-for impacts will be paid for before and after the product is released to the market. Without such an understanding and a plan for funding the impact, it is unlikely that the effort will have a lasting effect [4]. With the intent to be financially sustainable, WHOlives.org chose to design, manufacture, and sell a well-drilling system that would generate income to run the organization. To track financial sustainability, WHOlives.org has used a simple cash flow analysis. The cashflow history is shown in Fig. 6. The model includes the following terms: n_{d_v} is the number of drills invoiced for month, n_{w_v} is the number of drawings invoiced for month, I_t is the total income for month, I_{d_v} is the income from the invoice of one drill, I_{w_v} is the income from the invoice of one set of drawings, I_o is the income from donations, E_t is the total expenses for month, E_c is the expense from the cost of goods sold, E_h is the expense from operating overhead, E_s is the expense from salaries, and C_i is the cashflow for i-th time period.

The cashflow for the i-th time period is

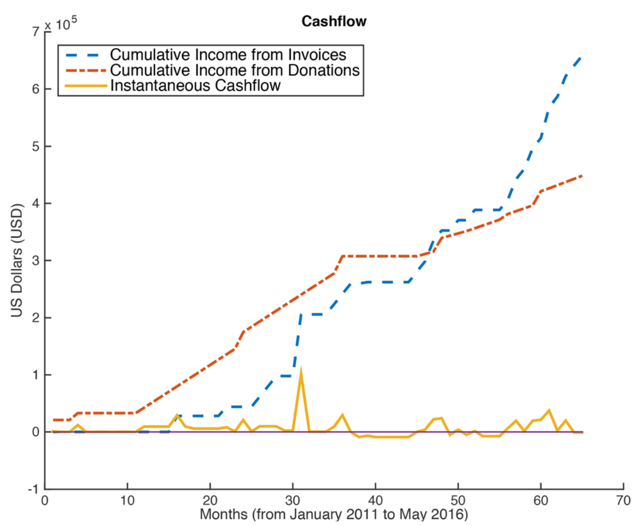

Fig. 6 Time series plot showing incomes and cashflow. Zero income shown as baseline.

$$C_i = I_t - E_t \tag{11}$$

where the income and the expenses for each period are calculated as follows:

$$I_t = (I_{d_v} * n_{d_v}) + (I_{w_v} * n_{w_v}) + I_o \tag{12}$$

$$E_t = (E_c * n_{d_v}) + E_h + E_s \tag{13}$$

The values for E_c, E_h, and E_s vary for different times during the past 5 years, as shown in the Appendix (Table 3). This data comes directly from WHOlives.org's records.

WHOlives.org priced the drill so that it would cost less than creating one borehole using traditional drilling methods, making it a more attractive option to an NGO than paying for a single well. The price is also affected by the cost of producing the drill. In Tanzania, a traditional well costs between \$15,000 and \$20,000 USD so they started selling Village Drills for \$14,000 USD, then increased to \$16,000 USD and finally to \$18,000 USD. The increases in price are largely because of higher quality drill bits being included in the drilling system.

WHOlives.org has received a total of \$658,500 through drill invoices, and a total of \$448,375 to support development, start-up, and other operational costs.

2.9 Uncertainty Analysis. We recognize that modeling the impact of the Village Drill is not trivial. It requires WHOlives.org to estimate values for the models' input parameters. We also acknowledge that there will be uncertainty regarding the accuracy of this and any estimation. For this reason, it is essential to the Village Drill case study that the uncertainty of the impact analysis be quantified and used to draw conclusions with higher levels of confidence than can be done with a deterministic analysis alone.

For the analysis carried out in this paper, three types of estimations were used: those made about the entire set of drills using data from only a sample; those made about all time periods using data from only a sample of periods; and those made to the best of our ability even though that ability is known to be imperfect.

Table 2 shows the estimated mean and standard deviation for the eight input parameters (lower portion of table) used to calculate the four primary impact measures (upper portion of table). The choice of mean values for each of the inputs was discussed in Sec. 2 of this paper. The term $\Delta n_{d_{os}}$ represents the difference between the number of drills believed to be out of service and those actually out of service. This term is added to Eq. (1) when the uncertainty analysis is carried out. The standard deviations were chosen carefully, based largely on experiences gained from 5 years of manufacturing/sales/distribution/drilling and on straightforward reports from the WHOlives.org drilling teams. After the mean of each value was chosen, consideration was made as to how much larger and smaller it could actually be at the extremes. In each case, a Gaussian distribution was assumed and the amount larger was divided by three to calculate the standard deviation.

Table 2 Uncertainty analysis results (including all time periods)

Measure	Mean	Std dev	97.6% conf.	99.9% conf.
n_{w_s}	458	101.51	≥255	≥154
n_{pops}	190,510	43,838	≥102,830	≥58,996
$n_{\text{pops}_{\max}}$	316,670	72,862	≥170,940	≥98,082
n_{pmws}	4,201,900	1,040,700	≥ 2,120,400	≥1,079,600
Input	**Mean**	**Sth dev**		
n_{bpm}	1.25	0.25		
n_{hub}	500	33		
n_{rim}	160	11		
$\Delta n_{d_{os}}$	0	1		
f_{hub}	0.78	0.03		
f_a	0.06	0.0066		
l_{mbf}	10	1		
p_{fms}	0.4	0.033		

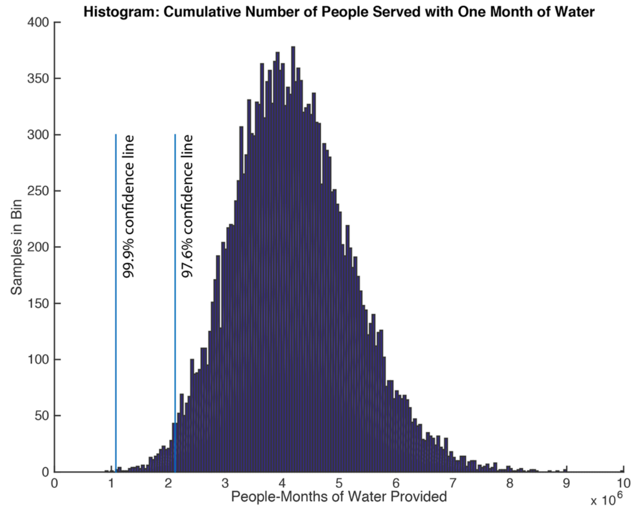

Fig. 7 Histogram resulting from the uncertainty analysis carried out on the cumulative number of people-months of water provided (n_{pmws}). The mean and standard deviation for this data are shown in Table 2.

A Monte Carlo simulation, using 200,000 samples, was carried out to better understand how variations in input parameters translate to the primary impact measures. The result of the simulation is shown in Table 2 for each of the four primary impact measures, and in Fig. 7 for the cumulative number of people-months of water provided.

The right side of Table 2 shows the final stage of the uncertainty analysis. Here the values for the primary impact measures are provided based on 97.6% and 99.9% confidence intervals. These numbers can be interpreted by considering the confidence lines shown in Fig. 7. We are 97.6% confident that the actual value for *people-months of water provided* is in the region to the right of the line labeled 97.6%.

3 Discussion and Conclusion

This paper has presented a case study on the Village Drill. The purpose of this case study was to present unobscured and unembelished facts and figures about the actual development and sustaining of a product engineered for a developing world market and setting. Our intention has been to present the drill and its data as a way of providing a more complete accounting of how impact is measured and the product is sustained after the bulk of the product development is complete. Additional information about the Village Drill can be found at the official website.[2]

It is worth returning to the case study's question: *What impact has the Village Drill had on water-poor individuals?* Using a nondeterministic analysis, this study concludes with 97.6% confidence that over 170,000 people have been impacted (via access to drinking water) by the Village Drill, and that over 2 million people-months of water have been provided. The Village Drill has done this by producing over 1000 boreholes, 761 of which have led to water. While doing so, the Village drill has employed 238 people for a total of 5838 months of employment.

In the literature surrounding engineering for global development, case studies with years of data post market-introduction are rare. Nevertheless, when authors have access to the data and organizations are willing to share, such cases should be told and used to inspire and inform successful engineering for global development.

[2]www.villagedrill.com

They can be a basis for comparison and the venue for discussion and growth within the community. We welcome constructive discussion—in favor or against the efforts undertaken for the Village Drill.

There are several important observations that can be made based on the data presented in this case study. Some of our observations include:

(1) Accounting: There is a substantial benefit to reporting on the engineering for global development efforts *after* there is data to describe the actual challenges and impacts. This is markedly different than reporting on development efforts with only an initial field study as evidence of impact.
(2) Evolution: Impact analysis can and should influence the ongoing evolution of the product. Impact analysis indicates whether a product and the system that supports it does what it is supposed to do. For the Village Drill, the analysis has resulted in various considerations for improving the drill and the program that supports it. For example, the data gathered shows that the average number of boreholes created per month per drill is 1.25; and since it takes approximately three days to drill a borehole, improvements in product cost or transportability, and/or improvements in the workforce can be made that will result in reaching more drill sites throughout the month and therefore improve the Village Drill impact.
(3) Sustaining: There is a significant amount of postengineering support that needs to be given to a product engineered for a developing world setting and/or market. Figure 2 shows 17 field trips taken by WHOlives.org to strengthen the training, sales, manufacturing, distribution, and other aspects of the product. Including such information is a valuable part of case studies because too many engineers fail to consider the costs (financial, temporal, and human) of supporting the design after an initial field study.
(4) Timing: For many of us, it is difficult to envision the timing of a project centered on engineering for global development. Though it is only one case, and timelines change case by case, the timeline shown in Fig. 2 provides useful information not found in the engineering for global development literature. It shows, for example, that only a few weeks passed from the founder's first trip to Africa before they founded WHOlives.org. And that within a few months they connected with strategic partners to develop the drill. It shows that the bulk of the product development and engineering took place in less than 8 months. An interesting insight that can be gleaned from Fig. 2 is that WHOlives.org was focused on being successful in Kenya and Tanzania before attempting to expand out to 13 other countries.
(5) Unidealized: Without the knowledge gained from struggling to sustain a product designed for the developing world, it is easy to idealize the conditions of its impact. This case study illustrates this in a valuable way. Any initial estimates of product impact would likely not consider realistic conditions such as wells with pumps that fail to get serviced and subsequently fail to provide water. As another example, it would have been easy to assume the traditional value of every well serving 1000 people, without 5 years of experience that show the numbers to be smaller where the Village Drill is being used (500 people for a well in a village center, and 160 people for a well placed in the outskirts of a village).
(6) Uncertainty: There is uncertainty in the data related to products engineered for the developing world. This uncertainty must be accounted for so as to put into perspective the conclusions drawn. The uncertainty analysis presented as part of this case study shows a large amount of uncertainty. Without doing such an analysis, one would expect the uncertainty to be smaller and therefore (erroneously) place more value on the deterministic study presented earlier in the paper. Though the uncertainty is large, it is quantified. Such analysis allows the authors to state with a certain degree of confidence that Village Drill impact is quantifiably positive.
(7) Assessment: The data presented in this paper can be used to perform other assessments that may be useful to promote the cause of engineering for global development. For example, the product development team for the Village Drill spent approximately 2000 man-hours conceptualizing, engineering and testing the Village Drill. That effort has had a quantifiable social impact; using the data provided in Table 2 for 97.6% confidence, we can say that for every engineering hour spent, 1060 people-months of water have been delivered. Or using the data presented in Table 1 we can say that a month of drinking water was delivered for $0.27 USD per person. Such information can play an important role in fundraising and motivation.

We believe that these kinds of observations are generally missing from the literature surrounding engineering for global development. We also believe that when case studies such as the one presented in this paper are shared in the archival literature it provides an important basis for comparison and a valuable venue for discussion. This is particularly needed in a field of growing interest such as *engineering for global development* and *design for the developing world*.

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Nomenclature

Productivity Measures

n_d = number of drills produced in total
n_{b_t} = number of productive boreholes drilled in total
$n_{b_{pi}}$ = number of productive boreholes drilled during time i
$n_{d_{si}}$ = number of drills in service, for time period i

Primary Impact Measures

n_{popsi} = number of people served (drinking) during time period i
n_{pmws} = number of people-months of drinking water provided in total
$n_{w_{si}}$ = number of wells in service during time period i
$n_{\mathrm{pops}_{\max}}$ = unique people served (drinking) in total

Secondary Impact Measures

n_{asi} = number of acres served (irrigation) during time period i
n_{amws} = number of acre-months of irrigation water served in total
n_{popei} = number of people employed operating drills during time period i

n_{pme} = number of people-months of employment created in total (operating drills)

Input Parameters

f_a = fraction of wells used to irrigate acreage
f_{hub} = fraction of wells serving village centers (hub)
f_{rim} = fraction of wells serving village outskirts (rim)
l_{mbf} = life expectancy (in months) of hand pump before first service required
l_d = life expectancy (in months) of drill
n_t = number of months past since start of project
n_{apw} = number of acres (average) irrigated per well
n_{bpm} = number of boreholes (average) per month a drill creates
n_{hub} = number of people (average) served by borehole at village center (hub)
n_{popepd} = number of people employed per drill
n_{rim} = number of people (average) served by borehole in village outskirts (rim)
$n_{d_{osi}}$ = number of drills out of service during time period i
n_{d_r} = number of drills retired in total
p_{fms} = probability of hand pump receiving first service

Subscript Notation

$[\ ]_{[\ ]i}$ = indicates $[\ ]_{[\ ]}$ for the i-th time period

Appendix: Raw Data

The raw data used in this case study is provided in Table 3. This data is included so that the impacts and plots can be recreated and so that others can use the Village Drill case study as a basis for further research. We note that COGS are the cost of goods sold, meaning how much it costs WHOlives.org to manufacture

Table 3 Raw data used in the Village Drill case study

Time period (month)	Drills added to fleet (number)	Known idle drills (number)	Drill price (USD)	COGS (USD)	Drawings sold (number)	Drawing price (USD)	Donations (USD)	Overhead (USD)	Salary (USD)
1	0	0	0	0	0	0	21,000	20,000	0
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	12,000	0	0
5	1	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	9375	0	0
13	3	0	0	0	0	0	9375	0	0
14	0	0	0	0	0	0	9375	0	0
15	0	0	0	0	0	0	9375	0	0
16	2	0	14,000	8200	0	0	9375	0	0
17	0	0	0	0	0	0	9375	0	0
18	0	0	0	0	0	0	9375	3500	0
19	0	0	0	0	0	0	9375	3500	0
20	0	0	0	0	0	0	9375	3500	0
21	0	0	0	0	0	0	9375	3500	0
22	1	0	16,000	8700	0	0	9375	3500	5000
23	0	0	0	0	0	0	9375	3500	5000
24	0	0	0	0	0	0	29,375	3500	5000
25	0	0	0	0	0	0	9375	3500	5000
26	1	1	18,000	9000	0	0	9375	3500	5000
27	1	1	18,000	9000	0	0	9375	3500	5000
28	1	1	18,000	9000	0	0	9375	3500	5000
29	0	1	0	0	0	0	9375	3500	3500
30	0	1	0	0	0	0	9375	3500	3500
31	6	1	18,000	9000	0	0	9375	3500	3500
32	0	1	0	0	0	0	9375	3500	5500
33	0	1	0	0	0	0	9375	3500	5500
34	0	1	0	0	0	0	9375	3500	5500
35	1	1	18,000	9000	0	0	9375	3500	5500
36	1	1	18,000	9000	0	0	29,375	3500	5500
37	1	2	18,000	9000	0	0	0	3500	5500
38	0	2	0	0	0	0	0	3500	5500
39	0	2	0	0	1	2500	0	3500	5500
40	0	2	0	0	0	0	0	3500	5500
41	0	2	0	0	0	0	0	3500	5500
42	0	2	0	0	0	0	0	3500	5500
43	0	2	0	0	0	0	0	3500	5500
44	0	2	0	0	0	0	0	3500	5500
45	1	2	18,000	9000	0	0	0	3500	5500
46	1	2	18,000	9000	0	0	4000	3500	5500
47	2	2	18,000	9000	0	0	4000	3500	5500
48	1	2	18,000	9000	0	0	24,000	3500	5500
49	0	2	0	0	0	0	4000	3500	5500
50	1	8	18,000	9000	0	0	4000	3500	5500

Table 3. *Continued*

Time period (month)	Drills added to fleet (number)	Known idle drills (number)	Drill price (USD)	COGS (USD)	Drawings sold (number)	Drawing price (USD)	Donations (USD)	Overhead (USD)	Salary (USD)
51	0	8	0	0	0	0	4000	3500	5500
52	1	8	18,000	9000	0	0	5000	3500	9000
53	0	8	0	0	0	0	5000	3500	9000
54	0	8	0	0	0	0	5000	3500	9000
55	0	8	0	0	0	0	5000	3500	9000
56	1	8	18,000	9000	0	0	10,000	3500	9000
57	2	8	18,000	9000	0	0	5000	3500	9000
58	1	8	18,000	9000	0	0	5000	3500	9000
59	2	7	18,000	9000	0	0	5000	3500	9000
60	1	7	18,000	9000	0	0	25,000	3500	9000
61	3	7	18,000	9000	0	0	5000	3500	9000
62	1	7	18,000	9000	0	0	5500	3500	9000
63	2	7	18,000	9000	0	0	5500	3500	9000
64	1	7	18,000	9000	0	0	5500	3500	12,000
65	1	7	18,000	9000	0	0	5500	3500	12,000

the drill. The column labeled overhead provides the general operating expenses not including salary expenses. The column labeled salary provides salary expenses.

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