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Nine Principles for Design for the Developing World as Derived From the Engineering Literature

This paper reviews the findings of several engineering researchers and practitioners on the topic of design for the developing world. We arrange these findings into nine guiding principles aimed at helping those who are searching for effective approaches for design for the developing world. The findings reviewed come from the mechanical engineering discipline, as well as from other engineering and nonengineering disciplines. For each principle, we provide references to various studies as a means of supporting the principle. We also provide a detailed example of each principle. Based on our own experience and based on the many papers reviewed, we provide a succinct list of suggestions for using each principle. Finally, we relate these nine principles to traditional design principles. Ultimately, we believe that the principles introduced here help overcome the challenges of design for the developing world, which are often dominated by designer unfamiliarity with poverty and foreign culture and the constraint of extreme affordability. [DOI: 10.1115/1.4027984]

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1 Introduction

Twenty percent of the world's population lives on less than $1.25 a day [1]; a stark contrast can be made to the average mechanical engineer in the United States, who earns enough to live on $283.55 a day [2]. These resource-poor individuals face significant life challenges including lack of clean drinking water [3–12], chronic hunger [13–15], inadequate health care [16–18], short life expectancy [19], inadequate housing [20], poor education [21–23], and lack of sanitation [24–27]. There is no shortage of want for these basic needs, and there is no shortage of opportunity to deliver as resource-poor individuals, which include the individuals making less than $1.25 a day, represent a $5 trillion market [28]. Many have observed and reported on the tremendous opportunity for business in these markets [29–39]. There is a shortage, however, in our understanding of how to effectively serve this market in a way that produces a lasting impact; many decades of effort has gone into trying with varying degrees of success. This paper reviews a portion of that work and articulates principles from the recurring themes, experiences, and conclusions of many different people.

In the past decade, there has been a surge of effort to reach resource-poor markets from leaders in business, social science, international development, and engineering. Most prominent in the engineering literature is the work carried out by electrical and civil engineers to design and install electrical, water, and sanitation systems for resource-poor communities [40–47]. In contrast, very little work has been published in the area of product design for resource-poor individuals [48–51]. Considering the life challenges listed above, innovative products have the potential to make a significant impact. The term product is used in this paper to describe any consumer good that is purchased by an individual or household. This includes medical products, income-generating products, mobile communication products, educational products, or any other products that make life easier or more enjoyable for the purchaser in some way. While mechanical engineering is not the only professional field with training in product design, mechanical engineers are well-trained in mechanical design, optimization, and manufacturing techniques—all of which may be needed to produce effective product solutions. Unfortunately, the opportunity and urgency to find solutions that alleviate poverty are far greater than the number of mechanical engineers currently involved.

There is a small subset of mechanical engineers who focus their research and professional efforts on alleviating poverty and their contributions have been valuable [4,7,14,50,52–62]. But greater impact is needed. Over the past decade, interest in design for resource-poor individuals has grown among students and professionals [63]. Engineers without Borders membership in the US, for example, increased 500% between 2005 and 2011 [64] and the Editor-in-Chief at ASME Magazine describes product design for the developing world as an area of research "worth pursuing" in 2011 [65]. Unfortunately, a generalized set of guiding principles to support these growing engineering interests is absent from the literature and common practice.

In this paper, we review the findings of several engineering researchers and practitioners on the topic of design for the developing world. We arrange these findings into nine guiding principles aimed at helping those who are searching for effective approaches for design for the developing world. We also provide a critique of the nine guiding principles and describe how they relate to traditional design principles.

We define a design principle as a fundamental proposition used to guide the design process. The principles in this paper are not suggestions or activities the designer should complete, they are assertions that can guide the designer to a more effective outcome. The principles do not explicitly say what should be done; they simply guide the engineer as decisions are made. They are not exclusive to the developing world, but the literature suggests that it is extremely valuable to consider them and that their application is different in subtle ways than their application in the developed world. Although principles are not guaranteed, and at times they should not be followed, they should always be considered [66].

For each principle, we provide reference to various studies as a means of supporting the principle. We also provide a detailed example of each principle. Finally, based on our own experience and based on the many papers reviewed, we provide a succinct list of suggestions for using each principle.

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2 Nine Principles for Effective Design for the Developing World

In this section, we articulate and support principles related to design for the developing world—as derived from the engineering literature. We also provide illustrative examples and suggestions for how each principle can affect the day-to-day engineering of those involved in designing products for individuals in the developing world. The nine principles described in this section are:

(1) Co-design with people from the specific developing world context encourages designer empathy, promotes user ownership, and empowers resource-poor individuals.
(2) Testing the product in the actual setting is an essential part of design for the developing world, not merely a final step.
(3) Importing technology without adapting it to the specific developing world context is ineffective and unsustainable.
(4) Both individuals in urban and rural contexts can benefit from poverty alleviation efforts.
(5) Women and children are more affected by poverty alleviation efforts than men.
(6) Project management techniques that are adapted to the specific developing world context enable a more effective and efficient design process.
(7) Products for the developing world have greater impact when contextualized, developed, and implemented by interdisciplinary teams.
(8) Cooperation with governments and local influencers contextualizes and enables poverty alleviation plans.
(9) There are existing distribution strategies that can be used to successfully introduce products into developing world markets.

Notice that each principle is fundamentally centered on the problem and solution context, where the context represents the circumstances that form the setting for the problem and/or solution. Importantly, we note that only when the context is established and understood can the solution finding process produce a valuable outcome. In other words, without an understanding of the context, it is impossible to know if a given solution can or should be implemented.

The remainder of this section is organized such that each subsection is dedicated to a single principle. In each of these subsections the following is given: (i) a brief articulation of the principle, (ii) a summary of the supporting literature, (iii) an example from the literature, and (iv) suggestions for using the principle.

2.1 Principle 1: Co-design With People From the Specific Developing World Context Encourages Designer Empathy, Promotes User Ownership, and Empowers Resource-Poor Individuals

2.1.1 Articulation. Co-design is the act of collaborative and egalitarian product development with resource-poor individuals. It (i) expands the designer's understanding of the needs of resource-poor individuals, (ii) expands the designer's understanding of the setting/environment where the products will operate, (iii) promotes design ownership (or the feeling that the idea or object belongs to the individual) among resource-poor individuals, and (iv) empowers them for current and future product development activities.

2.1.2 Support. Based on their experience gained through the codesign of toilet systems for Indian slums, Burra et al. [26] state that designing collaboratively with the community for which the product is intended leads to more impactful products. They point to resource-poor individuals as invaluable experts; these individuals know what their problems are and they know which solutions they prefer. Burra et al. observed such expertise when local users of the toilets helped design and build them. A lasting impact was achieved for the toilets because there was a strong sense of ownership for them among the resource-poor individuals. This ownership is evidenced by their willingness to pay a monthly fee so community members can be compensated to maintain the toilets. This ownership is due in part to their participation in the design process.

Co-design can be implemented to varying degrees. Nieusma and Riley [67] teach that simply talking to people in low-resource communities is only the beginning. In order for them to be truly committed to and excited about the resulting product, designers must involve resource-poor individuals in the concept generation, concept selection, and other important phases of product development [66,68–71].

Nieusma and Riley [67] use two case studies to describe that even when working with people from a developing country we must choose the right people within that country to work with. They most often worked with people from Non-Governmental Organizations (NGOs) and universities, and found that these people rarely lived in poverty themselves and therefore did not fully understand the challenges of poverty. This type of codesign approximates but does not fully embody the four hallmarks of codesign articulated by Murcott below [54].

Hallmark 1: The codesign partnership is egalitarian and synergistic. Hallmark 2: Recognition that resource-poor individuals have valuable expertise in surviving in low resource environments and in understanding local materials and networks. Hallmark 3: The codesign test lab is the actual environment where the final product is intended for use. Hallmark 4: The ultimate degree of codesign occurs when the collaboration is expanded widely, for example, under the framework of open-source innovation [72].

To have a more useful engagement with the stakeholders of their designs, Cruickshank and Fenner [73] believe that engineers need to "evolve and embrace some of the "soft skills" that lie at the interface of the physical sciences and the humanities/social sciences." George and Shams [55] also suggest this. Nieusma and Riley [67] observe that because engineers have a tendency to focus too heavily on technology, they can sometimes forget about other factors that significantly affect the impact of their work, such as social power relations, governmental constraints, and project sustainability. Novy-Hildesley [74] suggests that if engineers had more training in business, the impact of projects would be improved.

Witherspoon and Harris [75] say that we need to listen to what resource-poor individuals in the community actually want and need in order to be effective. Two other publications, not reviewed here, illustrate the value of this principle in the area of women's healthcare in developing countries [76,77]. There are also other publications that support the principle of codesign [59,78–82].

2.1.3 Example. As a more indepth example of this principle, let us consider more fully the toilet system described by Burra et al. [26]. Urbanization in India has presented many unique challenges. In some cities, as much as 50% of the population lives in informal slum housing with inadequate sanitation. The sanitation improvements the government undertook were infrequent, slow, expensive, and were designed without consulting people living in the slums which made the improvements ineffective. Burra et al. worked with women's cooperatives, an Indian NGO, and many government leaders to build toilet systems for over half a million resource-poor individuals in eight Indian cities. The strategic use of codesign led Burra et al. to this effective and impactful solution.

In an effort to protect their modesty, women in Indian slums often wait until dark to defecate which can cause gastric disorders and children are often pushed out of lines for the small number of available toilets by men. Because of this, women and children have the most to gain from improved sanitation. Burra et al. focused much of their efforts on the needs of women as they designed new toilet systems for these communities. After extensive surveys and interviews with people (mostly women) who use these toilets, they found that the most important features to the resource-poor community members were (i) that the men's and women's toilets be separate, (ii) that there be a water tank to ensure adequate water supply for hand washing stations and for cleaning the toilets, and (iii) that they would be built as inexpensively as possible to ensure that the largest number of people could be served. Interestingly, these features were not included in the government's previous designs. Furthermore, as the codesign efforts initiated by Burra et al. continued, many other innovative changes were added to the toilet design.

Throughout the process of designing and building, weekly meetings with community leaders, NGO workers, and government officials were held. According to Burra et al., this provided a channel for open communication, encouraged government officials to respect these previously marginalized community members, and decreased the occurrence of bribes and corruption during the construction phase. These interactions also gave female leaders confidence in their abilities and empowered them to make changes in their own communities. Women with no previous construction experience and little education began bidding for contracts to build the toilets and even began training women in other communities to do the same.

2.1.4 Suggestions for Using This Principle

(1) Respect the potential for resource-poor individuals to make significant design contributions.
(2) Immerse yourself in the culture of those for whom the product is intended. Optimally, travel to the intended setting and interact with them. Otherwise bring as much of the local setting to your current location as possible. Use personas (a representative profile to describe user behavior [83]), or locales (same concept as personas but the focus is a location, not an individual).
(3) Invite resource-poor individuals to join the design team; ensure that they are compensated for their effort; ensure that they have an appropriate and meaningful way to participate.
(4) Consider the complete product life cycle. This will require the design team to consider more fully the product's long-term integration into the intended setting, which includes defining the supply and distribution chains. Such considerations are facilitated through codesign.

2.2 Principle 2: Testing the Product in the Actual Setting Is an Essential Part of Design for the Developing World, Not Merely a Final Step

2.2.1 Articulation. Comprehensive simulation environments are not possible to create in a laboratory setting. The complexities of the physics, coupled with political, social, and cultural influences, are simply beyond our ability to simulate at high fidelity. As comprehensive testing is a part of effective product development, we must include field testing in the actual setting as part of the evolutionary process, not merely as a final validation of the concept.

2.2.2 Support. Bailis et al. [84] stress the importance of different validation tests at different stages of product development and implementation. Their experience in the area of biomass cookstoves illustrates that, although product development teams can have good results in the lab, the actual product impact is not usually measured. To begin such a measurement, teams could ask: (i) Does the product perform the same in the field as in our lab? (ii) Do the people who own the product actually use it? (iii) Do they use it the way we intended for them to use it? (iv) Have we done enough follow-up research to answer these questions?

As the number of engineering projects for the developing world increases, it is important for us to establish a method for evaluating the quality of the projects. Scott [85] provides a manual for project evaluation and George and Shams [55] introduce three questions that could be used to evaluate a design team's product: (i) Have the customer needs been met? (ii) Is the project sustainable and maintainable by the customer? (iii) Does the project respect the environment and make effective use of local renewable resources? Clearly, the value of mid-development field testing is indispensable in answering these questions.

Murcott [54] proposes a pattern for effective design for the developing world, which includes the recognition that field testing outweighs all laboratory simulations. Importantly, Harris and Marks [86] emphasize that carefully choosing the test/implementation site is critical to the product's success. For their work in the area of perinatal ultrasound, some key factors are the size of the client base, transportation to the clinic, availability of trained staff members, security of the equipment, and import/customs laws. Undoubtedly, attempts to fully simulate these factors in a laboratory setting are ineffective compared to field testing.

Candid discussions of successes and failures that support this principle are provided in [16,26,87–95].

2.2.3 Example. Ngai et al. [96] experienced the value of this principle as they worked on water filtration in Nepal. Arsenic and pathogen contamination are common in the well systems used by 90% of the southern Nepalese population. Arsenic contamination is as much as 100 times the recommended limit, and microbial contamination is the single largest cause of waterborne disease and death. Ngai et al. developed a filter to solve these problems and used the principle of field testing to achieve results with lasting impact. They started with clear goals for the filter related to ease of use for women and children, being low cost, and having a certain minimum flow rate. After a survey of existing technologies, 50 potential solutions were identified and eight were thought to be viable in rural Nepal. These eight were tested in a laboratory setting and the best three were chosen. Then, a total of 180 filters of these three types were distributed to households in Nepal and monitored monthly for 4 to 12 months. The technical, social, and economic performances of the filters were rigorously tested to determine which filter would provide the best solution for the target communities. After it was established that the Kanchan Arsenic Filter [96] was the best, Ngai et al. prepared the filter for local manufacturing in Nepal. One year later, over 80% of households were still using the filter daily and four years later, over 500 filters were in operation. The emphasis the team placed on testing—not just in the laboratory, but also in the field—was essential to the filter's impact.

2.2.4 Suggestions for Using This Principle

(1) Answer the questions posed by Bailis et al. [84]. Do we have enough information to understand if people are using the product the way we intended with the same results found in the lab?
(2) Answer the questions posed by George and Shams [55]. Does the product meet the customer's needs while being maintainable and respecting the environment and local resources?
(3) Allocate financial and time resources for field testing.
(4) Choose implementation and/or test sites carefully.
(5) Plan for field testing to be a mid-development activity, not a postdevelopment activity.

2.3 Principle 3: Importing Technology Without Adapting It to the Specific Developing World Context Is Ineffective and Unsustainable

2.3.1 Articulation. Technologies that have been successfully integrated into the developed world will not generally integrate into the developing world effectively or sustainably without first being adapted.

2.3.2 Support. Subrahmanyan and Gomez-Arias [28] emphasize that to enter low-resource markets it is not effective to simply remove features to make products less expensive, but it is effective and necessary to adapt and tailor products to be more relevant to the various needs of resource-poor individuals. In their efforts to design ultrasound devices for perinatal care, Harris and Marks [86] say that finding the balance between introducing new technology and respecting tradition is difficult. They also indicate that training models must be tailored to the new setting and personnel.

In the studies of Nieusma [97], he points out that imported technology did not yield the desired results because the context of the technology's development and use were very different. Nieusma and Riley [67] also say it is a difficult task to design something that works well for people in low-resource settings. Further, it is hard for engineers from developed countries to let go of their assumptions and focus on doing what is right for the resource-poor market.

Donaldson [98], however, conducted a study of local products and design activities in the formal, informal, and nongovernmental sectors in Kenya. She reports that products produced in Kenya fell into one of four categories: (i) imitation of foreign-designed products, (ii) imported designs, (iii) original basic design, and (iv) specialty design. Of the 55 products traced to the manufacturer, 54 were based on foreign designs and, therefore, were imported to some degree. She then explores the opportunities and constraints that encourage or discourage local design in developing countries.

After designing and attempting to establish local manufacturing for a manual mechanical shredder, Weiss et al. [99] made observations that support this principle. They observed that manufacturers in the developing world prefer to operate based on locally proven, established approaches instead of on less familiar, less certain approaches, even when those approaches have been highly effective in the developed world. This was due, in part, to the difficult challenge of overcoming cultural norms, such as those related to the concepts and expectations of production quality control.

A different yet equally interesting phenomenon in the developing world was encountered by Wijayatunga and Attalage [100] as they analyzed the use of electricity in rural Sri Lanka. They observed that using existing technology to reduce the effects of poverty can actually create unanticipated use-scenarios and demands for that technology—even a new use-scenario that does not reduce the effects of poverty. In the area of rural electrification, various researchers express concerns in support of this principle [21,89,101,102].

Other support from Akubue [103] indicates that importing large-scale technologies from the developed world does not generally help alleviate poverty in the developing world because these technologies are capital-intensive in a market with little capital. Further, costly labor-saving technologies are not valued in communities with excess labor capacity. Ultimately, according to Akubue, the importation of large-scale technologies encourages urbanization and can help resource-poor individuals in urban settings, but it creates a larger income gap between the rural and urban communities.

Alder et al. [16] share their experience with this principle. They traveled to the community and spent most of their time and effort training people to use the new technology. Community members also tracked their use of the new technology so Alder et al. could evaluate the effectiveness of importing it. It was generally successful, but the training had to be modified significantly to be appropriate for the needs of resource-poor individuals in that area. Witherspoon and Harris [75] offer several suggestions for evaluating the usefulness of a technology in a resource-poor community and provide questions that help designers challenge their own assumptions and make design decisions that are more effective for the intended users of the technology.

There are also examples of individuals, companies, and other organizations importing technology sustainably but these examples are not commonly found in the engineering literature and thus have not been reviewed here. Examples include mobile phones and plastic containers, which are ubiquitous in the developing world. Perhaps these have become ubiquitous because the technology itself is already adapted to the developing world. For example, mobile phone infrastructure costs are about 40% of the cost of building a landline network [104], and is therefore an appropriate choice for the developing world.

2.3.3 Example. Wijayatunga and Attalage [100] experienced the realities of this principle as they studied barriers to adopting clean and convenient energy sources. In many developing communities, the goal of electrification is to reduce the amount of biomass used in cookstoves so as to decrease harmful emissions and slow the rate of deforestation. Through their study of domestic energy sources in Sri Lanka, they found that the electrification of a community did not decrease the amount of biomass used for cooking. Because biomass could be gathered and did not have to be paid for, members of the community chose to use the electricity for things that only electricity could be used for such as lightbulbs, radios, and televisions. They continued to use biomass to cook because they were accustomed to working with it and preferred the way their food is prepared using that fuel. Instead of replacing other sources of energy as anticipated, electrification increased household demand for energy by providing access to new technologies. The electrification of this community had many benefits, but as far as reaching the goals of decreasing dangerous emissions and reducing deforestation, the importation of this new technology was ineffective.

2.3.4 Suggestions for Using This Principle

(1) Examine the various unanticipated use-scenarios for new technologies using tools such as Failure Modes and Effects Analysis [71].
(2) Understand the social context as well as possible ways to avoid implementing existing technology that will not integrate well in the developing world.
(3) Use robust design techniques [105] to develop products that will operate well without having to be produced with small tolerances.

2.4 Principle 4: Both Individuals in Urban and Rural Contexts Can Benefit From Poverty Alleviation Efforts

2.4.1 Articulation. Resource-poor individuals in rural settings have been the focus of significant poverty alleviation efforts [13,14,42,56,59,77,106]. Resource-poor individuals in urban settings, however, also benefit from poverty alleviation efforts.

2.4.2 Support. Fisher [14] states in 2006 that 70% of people living on less than \$1 a day are rural subsistence farmers. Because of this, efforts have focused on pumps and irrigation systems to help these farmers increase their income by helping them to grow more crops.

But in the last decade these resource-poor farmers have been increasingly moving to urban areas where they are met with inadequate housing, a lack of sanitation and access to water, and unemployment. The United Nations (UN) [107] reports that there are over 1×10^9 people living in urban slums and that this number is expected to double by 2030. Cruickshank and Fenner [73] state that 19 out of 26 cities with populations over 10×10^6 are in the developing world, as are 40 of the 61 cities with populations over 5×10^6. These numbers are only expected to increase. Cities with large populations living in slums are spread across South America, Africa, and many Asian countries, most notably in India where often half of the urban population lives in slums [26].

The scale and urgency of the problems faced by those living in urban poverty are overwhelming, but this new trend of urbanization offers some advantages. Programs that provide essential services like sanitation, healthcare, and employment opportunities can be more easily implemented in these densely populated areas. Products can be more easily marketed and distributed in this setting as well. Many slum communities have their own social organization and are generating innovative solutions to the problems that their communities face. With proper support from designers and engineers, solutions to their challenges are attainable [26].

2.4.3 Example. Morawczynski and Miscione [108] discuss the effects of mobile phone enabled banking on resource-poor individuals living in urban settings. More than 60% of the population in Nairobi, Kenya lives in one of Africa's largest slums, an area called Kibera. Only 17% of adults in this area are permanently employed and HIV rates are four times larger than Kenya's national average. People living here lack access to employment, water, sanitation, electricity, and many other services, including banking. Traditional banks are available in Nairobi, but resource-poor individuals can not usually afford the monthly fees and traditional banks are hesitant to open in Kibera because of security issues.

In March 2007, Safaricom introduced a banking service called M-PESA that allows resource-poor individuals to make deposits, withdrawals, transfers of money or phone credit, and even pay for goods at stores using their mobile phones. The majority of customers living in Kibera use this service to send money to family and friends in rural areas. Customers go to an M-PESA agent to deposit or collect their money, then receive a short message service message to their mobile phone confirming the transaction. After visiting several agents in the area, Morawczynski and Miscione decided to study the busiest agent in more depth. They observed her transactions and interviewed her and her customers. They learned that there are approximately 50–65 transactions per agent per day. There were typically more deposits than withdrawals, showing that resource-poor individuals are mostly using this service for remittances or to save their money. The agents reported that people would typically deposit large sums of money and then make small withdrawals throughout the month.

After one year, there were almost 2×10^6 registered M-PESA customers in Kibera and this number has continued to grow; the program was able to spread quickly because of the dense population in the urban setting. For some customers, this was their first exposure to the formal economy. This service was successful in Kibera because it was tailored to the needs of resource-poor individuals in this urban area.

2.4.4 Suggestions for Using This Principle

(1) Consider the opportunities that exist in both urban and rural settings for poverty alleviating products.
(2) Understand the unique conditions of both urban and rural settings and how they should influence the design.
(3) Thoughtfully choose to design the product for urban, rural, or both settings in order to have the greatest impact.
(4) Consider how the product will be purchased by and delivered to the customer in the chosen setting.

2.5 Principle 5: Women and Children Are More Affected by Poverty Alleviation Efforts Than Men

2.5.1 Articulation. Women and children are typically more vulnerable to the challenges of poverty than men and are therefore more affected by solutions to those challenges. Also, women are most often the ones who will bear the ongoing labor burden associated with poverty alleviating products.

2.5.2 Support. Burra et al. [26] explain that women and children in Indian slums are most severely affected by a lack of sanitation. Women are busy cooking in the mornings and cannot accompany their children to wait in line for toilets, so children are often pushed out of the way by adult men. The government-built toilet systems had no separation for women and men, so women had little privacy and were often harassed as they used the toilets. Because of this, women and children benefited most from the improved toilet design.

Murcott [54] explains that we should use engineering to create freedom from disease, poverty, and environmental degradation. She points out that "women and children are usually the most vulnerable and severely affected" by these kinds of problems. She also says that we should use engineering to create education, dignified work, and safety.

Women are often the key figure in establishing lasting solutions because they typically manage household resources. In many cases, if a solution is going to be successfully implemented, it will need to be accepted by the women. Biswas et al. [42] say that "women play a vital role in both cooking and energy management," and Ngai et al. [54] report that one of the criteria for their water filter was that it be acceptable to the women, since they are the typical managers of household water. Because of women's direct role in implementation, they are strongly affected by efforts to alleviate poverty—especially because women are most often the ones who will bear the ongoing labor burden associated with poverty alleviating products [13].

Women also face many challenges that men do not, the most obvious of which is bearing children. Harris and Marks indicate that maternal mortality is the leading cause of death for women of child-bearing age in developing countries [86]. Additionally, the responsibility of bearing and raising children prevents women from being employed outside the home, which leaves women (most certainly single mothers) vulnerable to poverty in more ways than men.

2.5.3 Example. Harris and Marks [86] embraced this important principle when they learned that maternal and infant mortality rates were significantly higher in developing countries—an issue that only directly affects women and children. Their solution to this problem was to select and implement a compact ultrasound device that would operate well in a low-resource setting. The selected compact ultrasound device was sturdy, designed to work with rechargeable batteries where electricity was not available or reliable, and was portable enough to be used in many situations, such as at bedsides, or in clinics and hospitals. The technology allows trained radiologists to determine the baby's position, make obstetric measurements, and gather other information that allows for more personalized medical care. Once these things are known, the radiologist can recommend transferring the woman to a clinic in the area that has the proper equipment and expertise to safely delivery her baby. This greatly increases the chance of survival for both the mother and the child. Harris and Marks went to a hospital in Nicaragua to donate one of these compact ultrasound devices and within an hour, expecting mothers were lining up for a chance to be examined. When Harris and Marks returned a year later, they found that annual maternal deaths in this small community had decreased from 12 to 5.

2.5.4 Suggestions for Using This Principle

(1) Ask community leaders to include women in codesign efforts.
(2) Plan activities that seek to discover the unique problems faced by resource-poor women and children in the community.
(3) Pre-evaluate how the implemented solutions will positively and negatively affect the women and children in the community.

2.6 Principle 6: Project Management Techniques That Are Adapted to the Specific Developing World Context Enable a More Effective and Efficient Design Process

2.6.1 Articulation. The design team's choice of project management strategy—and how it should be adapted to the specific developing world context—has a noticeable influence on the effectiveness and efficiency of the design process.

2.6.2 Support. George et al. [109] stress that investing time in project management is an important part of working with other groups, especially because of the ambiguity inherent in international development projects. As an essential part of project management, the role of each person needs to be clear and they need to be held accountable to it. George et al. also suggest that risk management strategies could be used to increase the likelihood of success. Understanding communication and cultural differences will also lead to a more successful project. Some communities, for example, are accustomed to oral communication only.

Reflecting on their multiyear project experience, George and Shams [55] promote the importance of effective project management. They provide useful tips including: (i) Begin the project with meaningful relationships: this comes through cultural education, humility, respect, and a preproject visit. (ii) Choose a project with care: this is best done with community and NGO involvement. (iii) Have an on-site development partner: US engineers are outsiders and it takes time to build trust; on-site development partners facilitate this. (iv) Include local manufacture and materials when executing the project: these are important for achieving lasting impact. (v) Select team members carefully: members should be well prepared for the experience and should expect to learn more than just design; select team members who can contribute or learn to contribute to social change. (vi) Plan for long-term involvement and encourage previous development team members to help mentor new members through the process. (vii) Define success criteria, which should always include community approval as a primary objective. Nieusma and Riley [67] also suggest that many NGOs and universities place a strong emphasis on education and team member exposure to new cultures. These goals do not always align with the goals of the community, which if ignored can lead to an increase in social injustice.

Additionally, George et al. [109] suggest that determining intellectual property rights at the beginning of the development project can be helpful. Blizzard and Klotz [110] suggest a framework for sustainable whole system design that could be applied to products designed for the developing world.

Many products designed for the developing world are designed by student teams in a university setting. This situation presents some unique challenges and several researchers have published their experiences working with students on this type of design project [111–115]. Other products are designed with the help and support of NGO workers and development workers in nonengineering fields. Other experiences and ways to measure the sustainability of projects are also found in the literature [116–118].

2.6.3 Example. George et al. [109] learned the importance of this principle working to help women in Mali produce shea butter and introduce it into international markets. Faculty and students at a US university started working with faculty and students at two universities in Mali and a Malian NGO. After several years of partnership, two other US universities were added to the project. This partnership of researchers, students, NGO workers, government officials, and resource-poor individuals created increased complexities in project management. George et al. learned through their experience that unclear project objectives and unclear role definitions for team members had a negative affect on effectiveness and efficiency of their projects and on how much people enjoyed being a part of the team. Having project goals and responsibilities in written form ensures that they are clearly articulated and that each team member can understand and reference them. George et al. report that increased care in communicating across institutions and cultures would have prevented repeated work and helped the subteams interact more effectively. Clear, written goals would have clarified expectations and prevented disappointment by helping all team members understand the university's semester schedule and the feasible possibilities for the various phases of the projects. They would also have helped all team members understand the iterative nature of mechanical design, the importance of prototyping, and the desire that local people may have to see a product working for someone else before they invest in it. George et al. suggest using project and risk management tools to overcome these challenges, but warn that these tools should not be imposed on the community. These tools do not always work well in other cultures and US engineers need to respect that cultural difference.

2.6.4 Suggestions for Using This Principle

(1) Consciously choose, adapt, and implement a project management strategy.
(2) Articulate everyone's responsibilities and hold all accountable.
(3) Understand, value, and adjust to different communication styles.
(4) Clearly establish success criteria, and use their measurement as a project management tool.
(5) Use risk and project management tools without imposing them on resource-poor communities.

2.7 Principle 7: Products for the Developing World Have Greater Impact When Contextualized, Developed, and Implemented by Interdisciplinary Teams

2.7.1 Articulation. Impactful solutions to poverty are most often identified and implemented by interdisciplinary teams. The multifaceted nature of poverty requires knowledge, skill, and sensitivity in social, political, technical, ecological, and economic factors. Teams with such knowledge, skill, and sensitivity produce products with greater impact than those that do not.

2.7.2 Support. Poverty problems have been characterized in the literature as social problems [119,120], political problems [22,121,122], technical problems [6,123,124], ecological problems [125,126], and economic problems [127–130]. Poverty problems clearly influence and are influenced by a diversity of factors. Consideration of these influences is most effectively carried out by interdisciplinary teams, where experts from multiple disciplines share ownership of ideas and cooperatively take responsibility for them [131]. Fortunately, interdisciplinary teams are not impractical since there is significant interest in poverty alleviation from many individuals in nearly all disciplines.

Although not often described as an interdisciplinary problem in the engineering literature [124,132,133], many researchers have reported the importance of interdisciplinary teams in achieving a lasting impact [13,14,55,67,73,74]. George and Shams [55] report on the importance of interdisciplinary teams and say that "to make sustainable change one must understand how to contribute to social change." They further express the frustration that "engineers don't have this training!" Fisher also supports this idea when he describes five steps to implementing a product in the developing world [14]. The five steps are: (i) Identify profitable new business opportunities. (ii) Design equipment. (iii) Establish a supply chain. (iv) Develop a market. (v) End market subsidies. Traditionally, engineers are only trained in the second step. To have a lasting impact, it is clear that poverty alleviating engineering efforts must be pursued in collaboration with individuals from other disciplines [88], or at a minimum with other disciplinary needs under consideration.

Nieusma points out that because engineers are well trained in dealing with technology, they often neglect other factors that affect the success of their products. These other factors include the culture and lifestyle of the user, social power relationships in the community, and the supply chain and distribution network of products [67]. Rarely is the engineering solution alone sufficient for lasting impact and even if the product works well technically, it has to be purchased and actually used by the customer before it can alleviate poverty.

The literature describes at least two ways for interdisciplinary knowledge, skills, and sensitivity to influence a project. The first way is through development of a team of experts from various fields [55]. The second, and least effective, is through training engineers in nonengineering activities that would otherwise be carried out by experts in nonengineering fields. The later often leads to lower quality work because of a lack of experience and intuition that comes with years of professional practice. It is, however, better for an engineer to consider how his or her engineering solution impacts or is impacted by social, political, ecological, and economic factors than it is for him or her to not consider them at all. Cruickshank and Fenner support this claim [73].

Novy-Hildesley [74] points out that foundations are a great resource for engineers because they are a hub through which all of these disciplines can converge. Foundations offer funds, but they can also support engineers by helping them establish business plans, marketing approaches, financial and other strategies, provide legal advice, and can offer useful connections in other fields.

The work by several other researchers also supports this principle [16,134–136].

2.7.3 Example. Postel et al. [13] share their experience with this principle. They report that 95% of the world's farmers live in developing countries and that the key to more successful farming is water management. The interdisciplinary team they established enabled them to successfully develop and distribute International Development Enterprises' (IDE) treadle irrigation pumps in rural India. One nonengineering element of the project that contributed significantly to its success was the use of Bollywood style movies rather than traditional printed ads to market the pump to rural farmers. These movies allowed information to be shared more quickly and be understood more easily. That was enough to convince people to take a risk and purchase the pumps and because the engineering was technically sound, many people were able to use the pumps to increase their farm's productivity. Engineers do not generally have training in marketing products and US engineers do not generally have training in marketing products to people in other cultures. Because Postel et al. decided to work with professionals in other fields they were able to have a greater impact. Having implemented a successful marketing approach, Postel et al. describe that the next challenges to overcome are finding a market for the increase of crops grown and increasing opportunities for microcredit [13]. Notice that these next challenges, which enable lasting impact, require a skill set not typically possessed by engineers. Because of this, interdisciplinary teams can provide products to customers that have a greater longer lasting impact.

2.7.4 Suggestions for Using This Principle

(1) Recognize that the poverty problem being solved is influenced by multiple disciplines and factors including social, technical, political, ecological, and economic.
(2) Capitalize on the wide-spread interest in poverty alleviation efforts to build an interdisciplinary team.
(3) Cultivate interdisciplinary attitudes on teams by seeking collective ownership of ideas and responsibility for them.
(4) Use foundations as a hub to connect with experts in other disciplines.
(5) In the absence of an interdisciplinary team, team members should seek knowledge, skill, and sensitivity in social, technical, political, ecological, and economic aspects of the project.

2.8 Principle 8: Cooperation With Governments and Local Influencers Contextualizes and Enables Poverty Alleviation Plans

2.8.1 Articulation. Poverty alleviation plans, both large and small, often require cooperation with governments and/or local influencers to be successful. This can be challenging and frustrating to design teams as socio-political objectives can often differ from the technical objectives of the design team.

2.8.2 Support. Decades of research has shown that rural electrification can help alleviate poverty, improve health, reduce drudgery, and increase literacy [137]. Infrastructural/systemic improvement, large or small, requires cooperation and/or funding from government and/or local influencers. Fulkerson et al. [137] present an ambitious poverty alleviation plan that requires significant government involvement to be successful. In their study of rural electrification, Fulkerson et al. introduce a 20 year, $100 billion plan to bring sustainable energy to 1 billion resource-poor individuals who do not currently have access to electricity. The plan allows each person 0.025 kW; the US usage per capita is 1.8 kW, and the world average is 0.3 kW. If this plan were implemented, it would open an entirely new market for low power consumption appliances and other products that engineers could design to help alleviate poverty. These products would be directly influenced by decisions made by governments and local influencers.

In their study of toilet systems in India, Burra et al. [26] provide a list of obstacles to sanitation development in slums. Interestingly, they found that some governments and land owners are hesitant to improve sanitation because this attracts more people to those slums, thus compounding the issue and making sanitation harder to maintain. Burra et al. imply that governmental bureaucracy is often a major obstacle to implementation; politics and over-regulated funding lead to inefficiencies and this can prevent products from getting to the people who need them most. It is important to observe that governmental objectives often focus on the population as a whole as opposed to individual needs. This may influence how products are introduced into the market.

After indicating that smaller-scale technologies that help many people in small ways are needed, Akubue [103] points out that one of the main obstacles to the spread of smaller-scale technology is "the existing power relations that favor advanced capital-intensive technology." He says that the political structure needs to change and adapt in order for small-scale technology to make a real impact. The political structure will affect the types of products that can be successfully implemented in a particular developing world setting and will affect the strategies used to implement the product.

As a different view, Margolin [63] says that real development does not come from individual products for individual families, but from higher production capacity that allow these developing countries to have a strong economy and compete in a global market. He uses Japan and South Korea as examples. This indicates that engineers can have the greatest impact by ensuring that the products they design are locally manufactured to stimulate the economy in the country they are designing for. Fisher [14] teaches that high-quality, low-cost production is needed to reduce product costs enough to be feasible for resource-poor individuals.

Harris and Marks [86] share their experience that bringing technology into a developing country can take a long time and can be expensive, with unexpected tariffs and bribes and that smaller devices are easier to get through customs. Harris and Marks teach that these obstacles should be planned for.

Considering government support from a different perspective, Uko [138] examines the value of government funding to send students from their own country to more developed countries to earn an engineering or science degree. The motivation for this is understandable as the US, Japan, and other countries have shown that engineering research is directly linked to economic prosperity. The ineffectiveness, as pointed out by Uko [138], is that most of the research these students do for advanced degrees has little to no application in their home countries. Further, the home governments often have no influence over the research performed by the students they fund. Uko also states that "effective engineering research cannot be conducted in isolation from the sociopolitical conditions of the country." Singley [139] also provides suggestions for training engineers in the developing world.

2.8.3 Example. An interesting example of both positive and negative government and policy maker influence is reported by Pamuk and Cavallieri [140]. They explain that in Rio de Janeiro, Brazil many people had moved from rural areas to favelas, or Brazilian slums. In the 1960s and 1970s, the government had many eradication and resettlement programs. They tried to eliminate all favelas within 10 years by moving resource-poor individuals out of the city's center to the outskirts, which unfortunately left them with little access to transportation, employment, sanitation, and many other necessities. This program ended when the government was overthrown. The resulting political instability leads to a decade of little formal policy for the favelas—a period known as "the lost decade" when there was minimal social development.

As the government stabilized, the favelas began to be upgraded under the Favela-Bairro Program. This program was intended to (i) provide adequate sanitation that would be maintained by the municipal government, (ii) spatially reorganize the favelas to better integrate them into existing city streets and community space, (iii) provide access to social services for people living in the favelas, and (iv) legalize land tenure. Programs such as mail service, trash collection, public lighting, and training programs for youth to learn marketable skills while improving their own communities were implemented. This helped give the program a more holistic approach and these upgrades were planned and implemented with frequent input from the people living in these areas. Here, the government intervened in a way that no other organization had the resources to do to improve the lives of millions of urban resource-poor individuals.

2.8.4 *Suggestions for Using This Principle*

(1) Before entering a community, find out who the local influencers are and how the design team should interact with them.
(2) Find out how bribes are handled in the context of the product and decide how the design team will deal with them.
(3) Find out how government and local influencers could impact the implementation of your product and form an alternative plan in case things don't go as expected.

2.9 Principle 9: There Are Existing Distribution Strategies That Can Be Used to Successfully Introduce Products Into Developing World Markets

2.9.1 Articulation. Various distribution strategies have been used over the past few decades to successfully introduce products into developing world markets. Strategies known to be successful should be used whenever possible and appropriate.

2.9.2 Support. To distribute a product successfully, engineers must first understand the market they are trying to reach. The literature describes three markets that product development teams typically focus on. They are:

(1) Products/systems designed for communities [63,141–144].
(2) Products designed for individuals [14,145].
(3) Products designed specifically to increase income [14,42,56,145].

There is some debate in the literature about the impact of product development activities for each of these markets. Akubue [103] supports the well-known approach of appropriate technology [63,141–144], which is a "development approach that is aimed at tackling community problems" as opposed to individual problems. It focuses on using the resources available (labor), not scarce resources (capital, skilled labor). The appropriate technology approach has not been without criticism. Akubue [103] provides a discussion about how critics point to many examples of failed projects to say that this approach is inadequate. He also finds other drivers—not the approach itself—that could have caused the failures.

In opposition to one of the appropriate technology tenets, Fisher [14] indicates that poverty-alleviating products need to be individually owned and cared for rather than community based to have impact. He and others argue that with community owned projects, there is no penalty for people who do not contribute and no reward for people who do.

Fisher [14] and Polak [145] express the belief that the only way to effectively alleviate poverty is to help people make money. Likewise, Biswas et al., [42] and Lewis et al., [56] support the notion of income-generating products.

Once a market focus has been chosen, distribution strategies should be considered. The literature suggests several successful strategies, including:

(1) Market the product in a way that is accessible to the user [13].
(2) Make the product as affordable as possible [13,146].
(3) Offer flexible payment options to increase product adoption [146].
(4) Use word-of-mouth to promote the product [13,14,146].
(5) Use market subsidies initially for new products [14].
(6) Include knowledge with every product sold [28].
(7) Sell the product in both developed and developing markets. Use the developed market sales to subsidize the developing market sales [74].
(8) Use philanthropies for legal, business, and marketing advice, as well as a source of useful contacts [74].

Postel et al. [13] describe that IDE's treadle pump was successful because they carefully considered their implementation strategy. IDE found significant success using movies instead of printed ads to promote their product. They also established the supply chain for the pumps and the parts for maintenance. Postel et al. considers these essential to development with lasting impact, because good ideas and designs won't have impact unless people actually buy and use them. Suggestions for encouraging product adoption are provided by Nakata and Weidner. They found that some factors that contribute to increased use of the product among resource-poor consumers are affordability, visual comprehensibility, flexible payment forms, and interpersonal promotions among others [146].

Fisher [14] also indicates that it is very difficult to have a successful for-profit business in this space because (i) resource-poor individuals are extremely risk averse, (ii) for-profit companies are forced to make a small profit from many people, and (iii) the initial cost to develop and sell a product is too high for resource-poor individuals to afford. He says that initial marketing subsidies help overcome these challenges.

Novy-Hildesley [74] describes distribution strategies involving philanthropic resources. Philanthropic resources allow poverty alleviating products to get to the people who need them the most by counteracting the market paradox in developing countries—large demand, yet no willing local or foreign suppliers. Unfortunately, most products wanted in the developing world are not marketable in the developed world; therefore, subsidizing costs to those in poverty by selling to both markets is effective in only limited situations. Aside from funding, philanthropic resources can also include mentoring in financial, marketing, legal, and other areas, as well as connections to other people working in this space.

2.9.3 Example. Subrahmanyan and Gomez-Arias [28] documented many effective distribution strategies for products designed for people in developing countries. One interesting strategy they discuss is that of including knowledge with every product sold. They describe CEMEX, a Mexican cement company that sells all the building materials someone would need to build themselves a house. There are many innovations in their business model and one impactful innovation is that they offer design consultation so consumers can learn how to design and build a sturdy and comfortable house. This allows people to be independent and build at their own pace as their income allows, but also gives them new knowledge that allows them to improve their own lives. Subrahmanyan and Gomez-Arias review Maslow's hierarchy of needs [147] and provide evidence for the fact that many people in developing countries choose to fill their higher-level needs at the expense of their lower-level needs. This is because in many foreign cultures community or family is more important than self [148]. For example, families will sacrifice things they need so they can send the children to private schools [28]. Providing knowledge with a product fills a higher need. This can lead to more implementation with more lasting impact than selling the product alone because people are more willing to spend their money if their purchase fills more than just a basic need.

Another example of including knowledge and self-development in a product is Danone's single serving yogurt in Bangladesh [28]. Women are trained to sell this product, but they are also trained in nutrition. As they sell their yogurt, they pass this knowledge on to other members of the community. Including knowledge with every product sold is just one of many distribution strategies that have been documented and can be used by designers to more sustainably implement their products.

2.9.4 Suggestions for Using This Principle

(1) Research the distribution strategies that have been successful for similar products in your specific setting.
(2) Examine the list of existing distribution strategies presented in this section and decide which is best for your specific project, if any.

3 How the Nine Principles Relate to Traditional Design Principles

In Sec. 2, we have examined the nine principles and have discussed their importance in the context of design for the developing world. To further explore the nature of these principles, we now categorize them in relation to traditional design principles often associated with the developed world. We use the three concentric ovals illustrated in Fig. 1 to facilitate this discussion. These ovals are discussed in Secs. 3.1–3.3 as a way of relating the nine presented principles to traditional design principles.

3.1 The Generic Solution Finding Process. In the center of Fig. 1, we see a generic representation of the basic solution finding process which consists of four steps: (1) requirement establishment, (2) solution generation, (3) solution evaluation and selection, and (4) solution embodiment. Generally in the design process, these basic solution finding steps will be executed often and at various times and scales. The process is often iterative where requirements, generation, and evaluation/selection steps may be executed multiple times to identify a desirable solution that merits embodiment in the product. The four step process

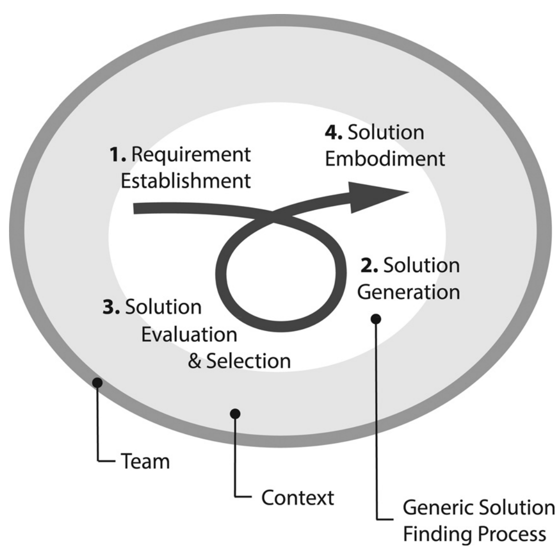

Fig 1. Three concentric ovals representing (i) a generic solution finding process (center), (ii) the context for the problem and solution (inner ring), and (iii) the team that contextualizes and develops the solution (outer ring). This figure facilitates the discussion in Sec. 3.

exists for the purpose of identifying and embodying desirable solutions to the design problem at hand.

The engineering literature provides various traditional design principles aimed at guiding the engineer through the design process. While we do not claim the review of these traditional principles to be comprehensive, we sampled several major works on the topic [66,70,71,149]. Through this review, we identified 35 unique design principles. Of these 35 principles, 30 apply to the generic solution finding process shown in the center of Fig. 1. These 30 principles are listed in the Appendix with citations. Of the remaining five principles, four apply to the context and are stated below. The context is shown as the inner ring in Fig. 1. The remaining principle applies to teams that value a diversity of expertise, shown by the outer ring.

We believe it is valuable to consider all of these traditional principles useful for developing world projects—they support finding a technically sound solution to the design problem. We also believe, however, that to have impact in the developing world, solutions must be both technically sound and desirable to those who will use or purchase them. Interestingly, at their core, none of the nine principles presented in this paper are about technical soundness as achieved by the solution finding process in the center of Fig. 1. Instead, they are fundamentally about the context of the problem and the solution—the understanding of which is necessary for achieving a desirable solution in a developing world setting.

3.2 The Problem and Solution Context. The inner ring of Fig. 1 represents the problem and solution context, hereafter referred to simply as context. Only when the context is established and understood can the solution finding process (center of Fig. 1) produce a valuable outcome. The context is the set of circumstances that form the setting for the solution. Without an understanding of the setting, it is impossible to know if a given product can or should be implemented.

It is important to recognize that requirements and context are not the same thing. To solidify this idea, consider this context (or circumstance that forms the setting): Many people in Burundi earn less than $271 annually. This context informs—but is not itself—a requirement. The informed requirement for a disposable medical device, for example, could be that it costs less than $0.05 for an impoverished Burundian to purchase. This requirement is informed by the low-income context.

In one respect, it is surprising to find very few principles in the literature that guide the engineer to understand the context for developed world products. On the other hand, this is not surprising since the engineer has typically lived his or her entire life in the developed world context and can relate to it naturally and intuitively. Creating products for the developing world, however, requires the engineer to understand and design for a context that is not at all natural to him or her.

Most engineering projects for the developing world do not fail because of the mechanics of the generic solution finding process. They fail because of a weak understanding of the context. This lack of understanding unfortunately leaves little opportunity for the solution finding process to produce a valuable outcome.

Several of the nine principles presented in this paper help the engineer understand the context for developing-world products. We now relate them to four of the traditional principles not yet discussed nor listed in the Appendix. These four traditional principles are listed below in italic text, followed by the principles from this paper, which apply to them.

Designers are responsible for the impact of their product on others [57,70]. This principle refers to the people for whom the product is designed. It includes those for whom the product is directly designed and those around them who may be indirectly affected by it. Four of the nine principles presented in this paper (in whole or in part) are fundamentally centered on how the product impacts people in the developing world context. They are:

- Principle 1 in part: Co-design with people from the specific developing world context promotes user ownership, and empowers resource-poor individuals.
- Principle 3 in part: Importing technology without adapting it to the specific developing world context is ineffective.
- Principle 4: Both individuals in urban and rural contexts can benefit from poverty alleviation efforts.
- Principle 5: Women and children are more affected by poverty alleviation efforts than men.

Design decisions affect all people in the downstream development [70,149]. This principle refers to everyone directly involved in the product development process. Three of the nine principles presented in this paper are fundamentally centered on how the decisions made during one stage of the product development process affects other product development efforts downstream. They are:

- Principle 3 in part: Importing technology without adapting it to the specific developing world context is unsustainable.
- Principle 6: Project management techniques that are adapted to the specific developing world context enable a more effective and efficient design process.
- Principle 9: There are existing distribution strategies that can be used to successfully introduce products into developing world markets.

Acquiring knowledge is costly and compromise regarding how much can be economically acquired may be necessary [70]. This principle refers to knowledge and understanding about the context and the solution. Two of the nine principles presented in this paper are fundamentally about how the acquisition of knowledge is more effective when centered on the actual setting and the people living within it. They are:

- Principle 1 in part: Codesign with people from the specific developing world context encourages designer empathy.
- Principle 2: Testing the product in the actual setting is an essential part of design for the developing world, not merely a final step.

Designers are responsible for the natural resources used in their products [70]. This principle refers to how the product will deplete, maintain, or reuse natural resources from the local developing world setting or from the global setting. Interestingly, we did not find a pattern of emphasis for this principle in the engineering-based developing world literature that we reviewed. Therefore none of the nine principles presented in this paper are fundamentally about our responsibility for our use of natural resources. This is not to say it is unimportant, or that it is never mentioned in the literature. It is to say, however, that it has not yet been a central repeated theme that engineering researchers have emphasized as essential to developing world efforts.

In this section, we have categorized seven of the nine presented principles as helping the engineer better understand the context for the problem and solution. Referring back to Fig. 1, we reiterate that only when the context (inner ring) is established and understood, can the solution finding process (center) produce a valuable outcome. To that end, it is essential that the context continually influence all parts of the solution finding process.

3.3 The Team. The outer ring of Fig. 1 represents the team of people who will discover the context (inner ring) and find solutions (center) to developing world design problems. The ability to discover that context well and identify highly desirable solutions efficiently is completely related to the composition of the team that attempts to do it. The two remaining principles presented in this paper apply to the team:

- Principle 7: Products for the developing world have greater impact when contextualized, developed, and implemented by interdisciplinary teams.
- Principle 8: Cooperation with governments and local influencers contextualizes and enables poverty alleviation plans.

The literature shows that teams consisting of multiple disciplines and local influencers are more capable of properly contextualizing the problem and can therefore generate more effective and appropriate solutions [70,71,149].

4 Concluding Remarks

As gleaned from the published literature, this paper has examined the work, experiences, and insight of various researchers and practitioners working in the area of design for the developing world. We have observed recurring themes within the examined work and summarized them in the form of nine principles for effective design for the developing world. Table 1 shows the nine principles in shortened form, with reference to the supporting citations. We feel that these principles—some of which are intuitive and some of which are not—represent the state-of-the-art in published design principles for engineers working to alleviate poverty.

We have also provided a list of suggestions for how to use each principle in day-to-day design and engineering practice. We believe that individually or as a compilation these lists provide a useful set of suggestions for any novice or expert searching for greater product impact and sustainability in the developing world. We have also shown how these nine principles relate to traditional design principles.

The work done to alleviate poverty through engineering could also be divided by product areas rather than by these principles. Some of the product areas with the most work related to them found in the literature are cookstoves and charcoal production [150–160], food processing [161–164], medical products and telemedicine [77,134,165–177], manufacturing systems [178–181], lighting [60,182–186], electrification [87,187–211], and mobile phones and information and communication technology (ICT) [106,212–218]. There are also several publications about poverty in general that may help us understand what role we as engineers can play in alleviating poverty [219–230].

Over a period of several years we have been involved in the design of 28 different mechanical products for resource-poor individuals in various places including Brazil, Peru, Tanzania, and India. Our experiences are consistent with the nine principles presented in this paper. At times, we have produced products with large impact because we followed these principles, and at other times we have failed to produce impactful products because we did not use these principles to guide our efforts. We agree with each of the nine principles and believe that they will help any engineer who wishes to design products for or with resource-poor individuals in the developing world.

Although the survey of the literature in the area of design for the developing world was comprehensive, the nine resulting principles are not. Undoubtedly there are other principles that can and should guide engineers as they design products for the developing world, but these are not yet found in the engineering literature. We believe that new principles are likely to be identified for each of the ovals illustrated in Fig. 1. For example, as more is learned

Table 1 Summary of principles

Principle (shortened)	Supporting citations
1. Empathy through codesign	[26,54,55,59,67,72–79,80–82]
2. Importance of in-context testing	[26,54,55,84–96]
3. Risk in technology importation	[16,21,28,67,75,86,89,97–103]
4. Rural and urban opportunities	[13,14,26,73,107,108]
5. Effects on women and children	[13,26,54,86]
6. Project management strategy	[55,67,109–118]
7. Interdisciplinary teams	[13,14,55,67,73,74,88,124,132–136]
8. Cooperation with government	[14,26,63,86,103,137–140]
9. Existing distribution strategies	[13,14,28,42,63,74,103,141–146]

about the efficiency and effectiveness of interdisciplinary teams solving developing world problems, new principles will come to the fore. The same is true for the problem and solution context, wherein we are likely to observe regionally specific principles emerge. Even new principles that guide the solution finding process may be identified and be specific to the developing world setting. As an illustration, it's possible that the well-known design for assembly principles related to reducing part count may have opposing principles that apply only in the developing world. Increasing the part count is arguably desirable in locations where the objective is to create jobs and grow local economy. In this sense, we believe that some traditional principles will be challenged and new, more appropriate principles specific to the developing world will be found.

We also believe there exists a difference between what appears in the archival literature and what nonpublishing practitioners do. For example, practitioners appear to invest more time and money in pre-engineering need finding through travel compared to academic researchers. This leads to holes in the literature and unanswered questions such as: What principles guide need finding for engineering in the developing world? What role does travel play for the engineer? And what principles guide the decisions to send an engineer on a pre-engineering need finding trip versus a mid-development validation trip versus an implementation trip at the end of a project? Principles that can be used to guide the decision making regarding these questions would be very valuable to engineers.

In gathering the nine principles, we have been careful to only present principles with multiple sources of support. We chose this approach because it produces a general pattern found to be true in multiple cases. As a drawback, this approach misses potentially valuable principles that are not broadly discussed. As the literature in this area grows, more and more evidence will be given for new principles. We believe, for example, that more principles will be identified regarding the designer's responsibility to the natural resources used in the product.

While the literature shows a pattern for the nine principles presented in this paper, there is still much that needs to be learned before we as engineers will become routinely effective at designing for the developing world. To that end, we invite and encourage academics and practitioners to critically evaluate their own developing world engineering experiences—and share that evaluation in the archival literature—so that they can influence others in their pursuit to design more impactful products for resource-poor individuals.

Acknowledgment

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Appendix

In Table 2, we list the traditional design principles. This list is not comprehensive but does include all the principles found in a few key traditional engineering design texts [66,70,71,149,231]. These principles are divided into the four steps of the generic design process.

Table 2 Traditional design principles for the four steps of the generic solution finding process

Principle	Citations
Traditional principles for requirement establishment	
Understanding the basic need before creating solutions leads to more effective and efficient solution generation	[57,70,149]
Good designers are aware of and influenced by existing designs	[70,149]
Risk is lowered when all functions are unambiguously specified, in form, parameters, manufacturing, and assembly	[71]
Proficient designers have a broad understanding and appreciation for multiple disciplines	[66]
Traditionalp principles for solution generation	
The best concept is typically found only after a large set of concepts are considered	[70,149]
Many generated concepts will be poor and not incorporated in the final design	[70,149]
It is difficult and inefficient to transition a poor concept into a good product	[70]
A strong concept is the foundation upon which a great product is built	[70]
It is more efficient to use a suitable existing component than to design a new one	[57,70]
When existing solutions are not suitable, they may become so through simple redesign	[70]
Opportunities for innovation exist at the boundary of feasibility	[70]
Traditional principles for solution evaluation and selection	
It takes a significant amount of thought and time to evaluate candidate solutions	[70,149]
There are many satisfactory solutions to every design problem	[70]
It is costly to keep many concepts in consideration	[70]
Tradeoffs exist and will need to be managed	[70]
Some important criteria can't be measured	[70]
Joint ownership in decisions is valuable to downstream development	[70,149]
Traditional principles for solution embodiment	
Complexity occurs primarily at interfaces	[70,71]
The number of interfaces increases with the number of components	[71]
Every fastener increases cost and decreases strength	[70]
How forces are transmitted through any part is important	[66,71]
Loads are effectively transmitted through triangles	[66,71]
Many mechanical designs experience failed amounts of elastic deflection before failed amounts of stress	[66,71]
Unwanted vibration can be reduced by reducing vibration at the source, changing the transmission of vibrations from the source to other parts, or by reducing the transmission	[66]
Whether a part in an assembly moves freely or binds is completely determined by the interactions of component weight, frictional force between components, and applied force between components	[66]
All components are positioned and constrained	[66]
It is not useful to overconstrain components	[70]
Shared modules across product lines are the basis (platform) for a product family	[66]
The most modular system is one where each function is embodied by exactly one module	[232]
Function determines form and form enables function	[70,71]

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