

Opinion

Toward a New Field of Global Engineering

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Abstract: The Engineer's role in addressing global poverty challenges has often been confined to village and community-scale interventions, product design and development, or large-scale infrastructure design and construction. Yet despite fifty years of these approaches, over half the world's population still lives on less than \$5.50 a day, the global burden of disease in low-income countries is overwhelmingly attributable to environmental health contaminants, and climate change is already negatively affecting people in developing countries. The conventional community, product or infrastructure focuses of development engineering is insufficient to address these global drivers that perpetuate poverty. The emerging field of Global Engineering can work to identify and address these structural issues. Global Engineering should be concerned with the unequal and unjust distribution of access to basic services such as water, sanitation, energy, food, transportation and shelter, and place an emphasis on identifying the drivers, determinants and solutions favoring equitable access. Technology development and validation, data collection and impact evaluation can contribute to evidence-based influence on policies and practice. Global Engineering envisions a world in which everyone has safe water, sanitation, energy, food, shelter and infrastructure, and can live in health, dignity, and prosperity.

Keywords: global engineering; sustainable development; sustainable development goals; poverty reduction

1. Introduction

Engineers are solutions-oriented people. Engineers enjoy the opportunity to identify a product or service need, and design technical solutions that can be deployed. Mission accomplished.

This model can be effective in high-income regions, where the engineering profession is complemented by a strong tax base leveraged to provide essential government services such as water, sanitation, electricity and roads, an enforced regulatory environment to maintain the quality and safety of these services, and business and consumer markets that pay for products and services. These complementary facets of society are often nearly transparent to the engineer, and engineering education does not typically include crash courses in economics or governance. As a result, engineers are poorly equipped to address or even recognize structural gaps when they exist in lower-income settings.

2. Global Context

Development optimism is abound. Pointing to the billions of people who have entered the middle class, the billions provided with vaccinations, and the often impressive accomplishments cited in the reports on the United Nations Millennium Development Goals and Sustainable Development Goals, the case is made that economic growth, life expectancy and overall prosperity are the inevitable outcome of current development policies and practice [1].

However, today over half the world's population lives on less than \$5.50 dollars a day [2]. The burden of disease in low-income countries is overwhelmingly attributable to environmental health

issues including air quality, water quality, sanitation and disease vectors including Malaria carrying mosquitos [3]. While the fraction of the world's population living in absolute poverty has decreased over the past fifty years, the absolute number of people in poverty is unchanged—about a billion people. If a child under the age of five dies, there is a 99% chance she was born outside of Europe or North America [4]. At the current rate of development, and assuming the same economic policies, it will take over 200 years for everyone in the world to earn at least 5 dollars per day. Furthermore, to achieve this level of growth, an increase in global production and consumption of resources of 175 times 2010 levels will be required [5].

Foreign aid and philanthropy are promoted as part of the solution to these chronic challenges. Indeed, over 160 billion dollars per year is provided by high-income countries to low-income countries in part to address these conditions [6]. Further, tallying up all financial resources including aid, foreign investments, trade, debt cancellation and remittances, over 2 trillion dollars was transferred to developing countries in 2012, the last year for which a full data set is available [7].

So why is poverty, and its associated conditions of contaminated water and air, rural isolation and lack of energy access, so stubborn?

One startling answer is that financial outflows—resources provided from low-income countries to high-income countries—dramatically exceeds inflows. Financial outflows, attributable to debt and interest payments, repatriation of corporate profits, and capital flight including trade misinvoicing and tax avoidance, accounted for over 5 trillion dollars in 2012 [7].

This three trillion dollars per year in total net outflows is 18 times the annual global foreign aid budget. In other words, low-income countries are net creditors to rich countries. Income inequality on this global scale is also felt within rich countries, and by individuals. Oxfam reported in 2017 that the richest eight people have more wealth than the poorest half of the world's population [8]. While many of these richest individuals are generous with their philanthropy, promoted at Davos, Aspen, on TED stages and through social impact investing, the concentration of wealth is only increasing.

Climate change is exacerbating and accelerating poverty in some regions of the world. The World Health Organization conservatively projects over 250,000 additional deaths each year between 2030 and 2050, attributable to climate change driven increases in temperature (heat waves), diarrhea, malaria, and malnutrition (crop failure) [9]. A further 100 million people could be pushed back into poverty by 2030 because of climate change [10]. Most of these deaths and hardships will be experienced in developing countries—those both least equipped to manage climate change and the among the populations least responsible for it.

Within this global context, it should not be surprising that engineers, while motivated to make a positive impact, are poorly trained and equipped to address these structural realities which swamp the contributions of an improved product or service.

Put simply—no new water filter product, social business sanitation service, elementary school rainwater catchment tank, electricity grid, or lecture to a local government on the importance of water pump maintenance will make a dent in a system that precludes countries from developing robust tax bases that can support governmental services.

3. The Past

The Engineer's first foray into the modern global development sector was through large-scale, top-down infrastructure including electricity grids, dams, roadways, and water management systems, often implemented in former colonies. The perceived failure of this model, as reflected in crumbling infrastructure in the 1970s, led to a pivot toward smaller-scale engagement, and models of community level participatory development.

The Engineer's response to community participatory development was provided by EF Schumacher, a British economist, who coined the term 'appropriate technology' in his book *Small is Beautiful* published in 1973. An appropriate technology, according to Schumacher, is one that is small scale, uses local materials, is energy efficient, environmentally sound, labor intensive, controlled

by the community, and maintained locally. This well intentioned approach sought to bypass the failures of large-scale development. Small-scale participatory development and appropriate technology models were adopted by many development agencies. In 2009, we promoted these models as the most impactful and appropriate way to train engineers to engage in poverty reduction efforts [11,12].

The terms 'global engineer' (Amadei, 2014) and 'development engineering' [13] have more recently entered the lexicon at the academic and professional levels. Since 2001, Engineers Without Borders-USA (EWB-USA) have engaged engineering students and professionals in extra-curricular and volunteer engagement in developing communities. This approach has been recognized as an important component of professional training [14]. However, more recently there is recognition that this appropriate approach is insufficient to train globally responsible engineers [15], and that (a.) rigor equal to any other engineering discipline should be introduced at the curriculum level and (b.) engineers must necessarily cross-train with other established development disciplines including global health, economics, public policy and social business [13].

Over the past nearly fifty years, appropriate technology and community participatory development has failed to eliminate or even substantially reduce the number of people living in poverty in developing countries. Meanwhile, the world has shrunk and technologies have advanced. Today, a development agency would not think twice about promoting mobile technologies and off grid solar energy, though neither fit the definition of appropriate technology. More current debates revolve around the appropriateness of importation of higher quality, lower cost often Chinese produced products such as water filters and cookstoves, at the expense of local producers, or the effectiveness of giving away these kinds of health products versus charging consumers a (often subsidized) fee.

Human centered design and product and service development, often linked to social business models, have also been promoted as an update to the role of the engineering profession in global development. 'Development engineering' was coined by experts at the University of California Berkeley in 2014 and advanced a model that links human centered design, multidisciplinary teams, user and community centric engagement toward product and service design [13]. Acknowledging the limitations of monodisciplinary approaches, the authors advance the premise that development engineering builds "on techniques from engineering, development economics, behavioral science, and sociology," and designs products and services on behalf of developing countries while addressing market barriers, institutional failures and promoting business models.

Furthermore, many engineering efforts on a community or product scale have required either volunteer or low-salaried engineering labor, which has the effect of reducing the professional depth of the contributions of engineers to global development. Meanwhile, larger-scale infrastructure efforts are often the purview of major engineering and technical contractors, (AECOM, CH2MHill, TetraTech, Chemonics) that offer competitive salaries, but may not be mandated or capable of addressing systemic development challenges.

Across these scales, an additional chronic limitation is the under-representation of engineers who are from low- and middle-income countries. Development programs instead often rely on short-term engagements by western engineers.

While case studies and attractive examples of successful products and services are laudatory, the reality remains that these are piecemeal patches to endemic structural challenges.

4. A Future

The role of engineers in contributing to global poverty reduction and the Sustainable Development Goals requires an upgrade. Luckily, there are several complementary academic and professional fields, including Global Health and Development Economics, that are better established, in track record and philosophy, from which we can learn.

Global Health as a field of study, research, and practice, is well established. The Consortium of Universities for Global Health states that the field, "emphasizes transnational health issues, determinants, and solutions; involves many disciplines within and beyond the health sciences and

promotes interdisciplinary collaboration; and is a synthesis of population-based prevention with individual-level clinical care,” and “places a priority on improving health and achieving equity in health for all people worldwide.”

Similarly, Development Economics, as embodied by the World Bank, is a field dedicated to studying and leveraging economic tools including taxes, trade, transfers, loans and investment to improving economic growth in low-income countries.

The Global Health and Development Economics communities are grounded in method and tool development, evidence generation and translation of findings into national and global policies. Many implementations, impact evaluations or research studies conducted by economics or public health professionals are designed to address immediate needs will generating evidence to inform policies and funding decisions. Publications, methods, tools and technologies are evaluated, tested and refined, and consensus is built through meta-analysis and dissemination.

Global Health and Development Economics are imperfect models. Often, implementations and evaluations are designed and conducted with foreign funding and foreign experts, which can have the effect of reinforcing autocracies and creating a “tyranny of experts” [16]. However, the professionalization of these fields has resulted in a high degree of influence on policy and the public.

We define Global Engineering as concerned with the unequal and unjust distribution of access to basic services such as water, sanitation, energy, food, transportation and shelter, and places an emphasis on identifying the drivers, determinants and solutions toward increasing equitable access to reliable services. Global Engineering envisions a world where everyone has safe water, sanitation, energy, food, shelter and infrastructure and can live in health, dignity, and prosperity.

We advance that Global Engineering can therefore be the professional and academic complement to Global Health and Development Economics—focused on broadly improving the tools and practice of poverty reduction, and deliberately including health, economics, policy, and governance as relevant dimensions, and requiring our professionals to be conversant in these fields.

5. Examples

The field of Global Engineering, while working toward improving policies and equity globally, need not be divorced from innovating solutions and designing technologies. Indeed, technological innovations can support knowledge generation, policy and public participation in acknowledging and addressing root causes of persistent poverty. This section provides several pertinent examples from a variety of institutions and applications, including those supported by the Mortenson Center in Global Engineering at the University of Colorado Boulder.

5.1. Remote Sensing

Space-based Earth observation instruments, while often funded, designed and operated to serve the particular interests of wealthy countries, can provide benefits to developing countries at minimal additional cost. The insights gained from the analysis of remotely sensed data can result in practical actions as well as informing policy and public response.

A compelling example has been demonstrated in east Africa. Average rainfall in east Africa has been declining over the past several decades. In parts of this region, average rainfall has decreased over 20% since 1990 [17]. As a result, millions of people living in the arid, drought prone regions of the East African Rift Valley, including parts of Ethiopia and Kenya, are facing significant threat from a lack of safe, reliable and affordable water [18,19]. The 2011 drought in East Africa caused food shortages for over ten million people and as many as 260,000 deaths [20,21]. The more recent 2016 drought in Kenya resulted in over 3 million people facing food insecurity [22]. These recent drought conditions represent an acute threat, and highlight the urgency of environmental changes driving water shortage and creating a public health and security emergency.

The USAID founded Famine Early Warning Systems Network (FEWS NET) works to combat the worst consequences of drought driven food insecurity. The FEWS NET model is based in part on

rainfall and crop health estimates using remote sensing data, forecasting food security stress based on estimated agricultural yields [23–25]. FEWS NET publishes food insecurity forecasts leveraged by national governments and international relief agencies to position food relief before the most severe consequences are felt by local populations.

Beyond the immediate, technocratic benefits of FEWS NET findings, are the implications of the repeated alarms raised by these food insecurity models. The forecasts suggest increasing severity and frequency of humanitarian crises, which may have the effect of drawing political and public attention to the unjust impacts of climate change.

The NASA and USAID funded SERVIR program similarly works to adapt satellite-based remote sensing toward mapping data, hydrologic and agronomic models, and the development of decision aids to assist regions of Africa, Southeast Asia and the Himalayas. These tools have assisted in water resource management, flood prediction, and land use planning, while building the capacities of developing countries to develop and manage these technical services [26–29].

5.2. Instrumentation

Many development programs, from household-scale interventions to large-scale infrastructure, rely on third party funders and lengthy processes for proposal development, implementation, and some measure of monitoring and evaluation. Despite increasing emphasis on the monitoring and evaluation phase, a reality of finite and time-bound funding often means that the medium- and long-term impact within developing countries is not provided as feedback to inform the decisions donors make.

This intent-impact information and knowledge asymmetry can, in part, be addressed through improvements in the technologies used to collect ongoing data on the performance of interventions, and the services delivered [30]. Technological innovations in the design, deployment and validation of instrumentation, and furthermore the analysis of the data generated, can be used to inform programs, policies and donors.

For example, ongoing activities in Ethiopia and Kenya are aimed at improving the functionality of rural water supplies, reducing the downtime between repair activities, and ultimately improving water services, reducing water insecurity, and reducing the impacts of drought. The intervention includes installing satellite and cellular connected sensors monitoring the runtime of rural electric pumps, and linking that data through algorithms to online dashboards. The data is intended to be used by regional maintenance providers, utilities, national government entities, and international donors to both enable and support increased prioritization of repair services [31].

While instrumentation is a technical intervention, the insights generated are intended to inform policymakers, local and national budgeting and donor decisions in an effort to recognize and address the major gap between funding available for infrastructure installation and funding available for operation and maintenance, on both the scale of the programs themselves, and through informing discussions on a global level.

This effort requires the participation of engineers from a broad range of disciplines, including civil, environmental, mechanical, and electrical engineering and computer science, integrated with expertise in governance, foreign aid, and community strengthening. A series of evaluations, including an independent impact evaluation, are currently studying these efforts. The instrumentation used has the unusual status of being both part of the intervention's theory of change, while also serving as the primary data collection tool used to evaluate the effectiveness of the intervention activities.

5.3. Impact Evaluation

In the past decade, there has been an increasing emphasis on using rigorously designed, independent experiments to evaluate development interventions. The academic fields of Global Health and Development Economics have been prolific in designing and administering rigorously designed experiments. Books such as *Poor Economics* that review the sometimes counterintuitive

results of these studies have catalyzed discussions among policymakers, national governments, donors, implementers and researchers as well as increasing participation from the public.

The results of these trials inform international policies, donor decisions and implementation designs, and leverage the best practices in academic research to build a body of knowledge over time. For example, a series of rigorous efficacy trials of chlorine interventions, including a multi-year, multi-million dollar water and sanitation trial funded by the Gates Foundation recently reported no effect on diarrhea among children under the age of two [32,33]. Meanwhile, other recent trials have shown considerable impact on diarrhea among children under five associated with household water treatment [34]. While in some ways providing contradictory results, the overall body of knowledge grows and consensus is reached over time on the most effective and appropriate health interventions.

Limitations of the most rigorously designed evaluations, randomized controlled trials (RCTs), include the often small scale of the studies, the constraints in adjusting the intervention during the study, and the challenges in generalizability. Further, the results of these studies often take many years to be analyzed and published.

Global Engineering may have a role in advancing impact evaluation methods that may be more adaptable to programs, scalable and more quickly actionable. Engineers do not normally conduct RCTs in the design, testing and validation of new technologies. Instead, engineers design standardized and customized testing routines, gather data on technology performance, conduct analysis, and build in safety factors. This approach, which is iterative and exploratory, is no less rigorous—as evidenced by the absence of RCTs supporting or refuting the effectiveness of parachutes [35]. Engineers can adapt these approaches to evaluating global development interventions, especially those leveraging technological interventions. Study designs that allow the iteration of the implementation may still collect credible data. This approach is aligned with Implementation Science, an emerging field in medicine and public health. Implementation Science works to close the “know-do” gap between the demonstrated efficacy of a given health intervention and the actual observed effectiveness when deployed operationally [36]. Implementation Science study designs can allow for iteration of implementations.

5.4. Standards Development

Engineering has a rich history of developing, validating, refining and implementing standards. These standards evolve based on evidence, best practice, and consensus building. Published standards can support objective evaluation of products and services. Within the global development space, engineers have contributed to standards for household drinking water products [37], household cookstoves [38], emergency shelters [39] and other products and services.

The development and support of standards is a valuable contribution by engineers to global development, and can be further applied to other areas of sanitation, energy, water, transportation and infrastructure.

5.5. Pay for Performance Contracting

There is emerging alignment between rigorous research studies and output or performance based incentives. These approaches can increase accountability and scale of effective interventions. Engineers have designed many of these systems. As part of a team, engineers designed the first carbon credit financed household water treatment programs, implemented in Kenya and Rwanda. These programs required private funding to implement, followed by monitoring and issuance of carbon credits tied to ongoing performance of the programs. These credits were sold to commercial and concessionary buyers including the World Bank [30].

More recently, Bridges to Prosperity (B2P), a US-based non-profit that designs and constructs pedestrian footbridges in developing countries and is led by civil and structural engineers, has started a transition from a reliance on charitable donations for one-off projects, to a scalable, accountable and financially sustainable outcome based model.

Isolation caused by lack of transportation infrastructure affects almost every facet of life for the rural poor. Without adequate transportation access, families cannot access schools, health care, employment, or local markets to sell and buy goods. The World Bank estimates that nearly a billion people worldwide lack access to an all-season road within two kilometers, illustrating the scope of the problem, and the challenge of addressing it at scale. B2P has constructed more than 300 footbridges in 20 countries, an infrastructure intervention that is cost-effective, durable, and relatively simple to scale. An economic impact evaluation of B2P's footbridges in Nicaragua found a 35.8% increase in labor market income attributable to the access provided by the bridges [40].

B2P's field program in Rwanda started in 2012 and has led to the completion of 47 footbridges that have created new safe access for an estimated 274,000 people. Over the next five years, B2P plans to construct approximately 350 footbridges in Rwanda. This rapid program growth presents an unprecedented opportunity for rigorous investigation of the effects of new footbridges on a number of key economic, health, agricultural and education outcomes for rural communities.

B2P's scale-up model is designed to combine funding from local and national governments in Rwanda, combined with both philanthropic as well as debt financing from international sources. Upon completion of the footbridges, and demonstration of the health and economic impacts, an outcome-based payment will be issued to B2P to repay investors and further expand their program.

5.6. Systems Engineering and Science

Engineers have recently recognized that the complex systems governing effective development must be considered when designing projects. In this direction, engineers have recently advanced "systems thinking", systems engineering, and inclusion of the role of governance and institutions in addressing basic service delivery [41].

Systems engineering has been particularly leveraged in the fields of water and sanitation [42,43]. USAID promotes a local systems framework for the development of water supplies, and design includes principles such as systems mapping, holistic design, monitoring and accountability [44]. The USAID Sustainable WASH Systems activity, led by the University of Colorado Boulder, is designed to characterize the systems behind WASH services across several programs in Uganda, Kenya and Ethiopia. The activity recognizes the past failures in providing reliable service delivery, and seeks to generate knowledge around the broader systems required to improve services. One element of the SWS model is the promotion and facilitation of learning alliances, which bring together actors at a district and local level to collaborate in identifying relevant service delivery relationships, material flows and leverage points and through collective action improving WASH services [45].

Similarly, the WASH Agenda for Change, supported by a network of influential donors and implementers, considers financial planning as an underpinning activity in promoting improved WASH services. The model also promotes collective action, and measurement of long-term service delivery achieved [46].

A potential limitation of systems approaches is that there is a continued focus on local actors and factors, while the broader implications of globalization are considered outside of the design envelope. Systems engineering would benefit from considering global trade imbalances, resource exploitation, and the unequal distribution of wealth which can preclude local governments from having tax-based resources as relevant factors when considering the relative influence of various factors in the sustainability of basic services.

5.7. Education

There are several emerging educational programs aligned with the motivations of Global Engineering. The Engineering for Change curriculum, offered online, was designed and curated by the American Society of Mechanical Engineers (ASME), with participation from the Institute of Electrical and Electronics Engineers (IEEE) and Engineers Without Borders-USA. The free online curriculum

offers introductory trainings for engineers seeking to apply their skills to global development challenges, including introductions to development history, practice, and local contexts.

At the university level, the Centre for Global Engineering at the University of Toronto is a cross-disciplinary research institute that focuses on areas of global need, including food and nutrition, water and sanitation, health and shelter. The Centre includes participation from all engineering disciplines in the Faculty of Applied Science and Engineering and works in both Canada and developing countries.

Similarly, our Mortenson Center at the University of Colorado Boulder has evolved from a model of scale appropriate technology design and implementation, to an emphasis on the development and validation of more broadly applicable methods, technologies and evidence generation. As reflected in our name change from “Engineering for Developing Communities” to “Global Engineering”, we seek to positively impact vulnerable people and their environment by improving development tools and practice.

Our areas of research include organizational theory and systems engineering, the development and validation of water, sanitation, energy, infrastructure and agricultural technologies and methods, design of service delivery models, impact measurement methods and technologies including instrumentation and remote sensing, and development of standards for engineered systems applied in disaster relief. The Mortenson Center curriculum includes opportunities to take short courses in complementary topics such as Global Health, Development Economics, remote sensing, statistical analysis, and impact evaluation. Our required field practicum embeds students with global development agencies for at least 3 months, with some students continuing to engage with these agencies for many years.

6. Forward Work

The role the engineer in addressing today’s global poverty challenges must be elevated. While village-scale interventions may have a positive impact on a community, product design may address some consumer demands, and large-scale infrastructure can, in the short term, fill gaps in basic services, the structural constraints that perpetuate poverty require structural solutions.

The field of Global Engineering can contribute to addressing these structural issues, through developing and validating methods, tools and standards that are broadly leveraged to address poverty reduction. Technology development and validation, data collection and impact evaluation can contribute to evidence-based influence on policies and practice. Remote sensing technologies are informing conversations about the unjust impacts of global warming. Data collection and analysis technologies support impact evaluations in generating robust findings on the effectiveness of interventions. Systems engineering is expanding the engineer’s lens to more broadly consider institutions, governance and financial planning in basic service delivery. Engineering education is embracing history, public health and policy.

Global engineers must be taught to consider the historical and present causes of persistent poverty, instead of perceiving poverty as simply a stage of inevitable growth that can be helped along with conventional technical solutions. This training will better inform the choices engineers make in placing their emphasis, and may move our sector away from a product and village level focus toward working to address the root causes of poverty. Unequal distribution of wealth and resources, and continued exploitation of low-income communities by the global economic system will preclude the effectiveness of small-scale programs and products.

Global Engineering should work to understand and address the unequal and unjust distribution of access to basic services and envision a world where everyone has safe water, sanitation, energy, food, shelter and infrastructure and can live in health, dignity, and prosperity. Yet, as much as any other profession, engineers have an opportunity to contribute to a more just and equitable world.

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