Silvia Hostettler · Eileen Hazboun
Jean-Claude Bolay *Editors*

Technologies for Development

What is Essential?

United Nations
Educational, Scientific and
Cultural Organization

uni Twin

UNESCO Chair in
technologies for development
Lausanne (Switzerland)

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

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ISBN 978-3-319-16246-1 ISBN 978-3-319-16247-8 (eBook)
DOI 10.1007/978-3-319-16247-8

Library of Congress Control Number: 2015935405

Springer Cham Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media (www.springer.com)

Preface

Since the dawn of the industrial age, innovative technologies have been viewed as instrumental in enhancing productivity, generating economic growth, and transforming living conditions for billions of people. These technologies are a priority for North–South development cooperation, empowerment, and poverty reduction.

At the Ecole Polytechnique Fédérale de Lausanne (EPFL), we believe that technological innovation can be a pathway to sustainable development. Indeed, innovative and well-adapted technologies are very powerful tools that can render development effective on a large scale for disadvantaged people.

EPFL has been active in development cooperation for decades. This embodies the institution's open approach to the world: An outlook where humanist values and a scientific spirit are combined to produce research that is guided by a sense of responsibility toward the major problems faced by people in the Global South. It reflects the long-established ties between Switzerland and other countries, which are expressed in various, complementary ways: admission of students from the South, partnerships with universities and research centers in Africa, Asia, and Latin America, and numerous internationally recognized scientific and technical products. Development cooperation also complements Swiss government policies and relevant national legislation.

In 2007, UNESCO bestowed the Chair in Technologies for Development on the Cooperation & Development Center (CODEV), thus increasing the coherence and visibility of EPFL's development cooperation activities and reinforcing its existing research, education, and capacity building activities.

Through the UNESCO Chair, EPFL seeks to further utilize its know-how and international renown to establish partnerships with developing and emerging countries as: It is at the cutting edge in many scientific domains and can therefore function as a relay to developing countries; its acknowledged expertise brings it into contact with many projects funded by development cooperation organizations; and it has close links with national and international scientific networks and can thus express its viewpoint on various development issues.

The strength of the UNESCO Chair lies in its dual capacity to orient EPFL laboratories toward specific development objectives and to conduct research and educational programs focused on international development. The biennial UNESCO Conferences on Technologies for Development, in particular, are rapidly turning into flagship events for CODEV, drawing an ever-increasing audience.

These conferences are highly successful in promoting research in technologies and innovation for developing countries. They create a platform for spirited discussion and scientific exchange, as well as increased awareness of state-of-the-art technologies and their potential in the Global South. North–South research partnerships are promoted, and diverse stakeholders and actors are encouraged to engage in cooperation projects by these events.

This volume brings together the best papers of the 2014 EPFL-UNESCO Conference on Technologies for Development (2014 Tech4Dev) and illustrates the key issues at the interface of technology, human, social, and economic growth. Case studies from Africa, Asia, and Latin America explore the development potential of technologies and discuss successful processes to develop and deploy them, as well as how to evaluate their impact.

EPFL envisions the future as a globalized society, where our responsibilities, as scientists and more broadly as academic institutions, are producing knowledge, innovative technologies, and high-level graduates that are aware, can adapt to global challenges, and are equipped to collaborate with our colleagues from the four corners of the world, especially where serious problems of survival, development, and progress remain to be solved.

Jean-Claude Bolay

Acknowledgments

The editors owe a debt of gratitude to many individuals and organizations who generously contributed their time, insight, and support. First, we would like to thank the members of the Scientific Committee and our Session Leaders who guided the conference preparation. They not only made the 2014 EPFL-UNESCO Conference on Technologies for Development (2014 Tech4Dev) a great success, but also laid the foundation for this publication.

We would also like to express our thanks to Prof. Philippe Gillet, Vice-President for Academic Affairs at the Ecole Polytechnique Fédérale de Lausanne (EPFL), for his presence at the Conference and unfailing support to the Cooperation & Development Center (CODEV).

By willingly sharing their considerable expertise and different outlooks, the speakers at the UNESCO Conference brought much food for thought to the table and substantially contributed to its success. Our heartfelt thanks go to Dr. Shashi Buluswar (LIGTT: Institute for Globally Transformative Technologies), Prof. Karen Scrivener (EPFL), Mr. Anil Sethi (Swiss Extension GmbH), Dr. Jean-Bernard Münch (Swiss Commission for UNESCO), Dr. Jean-Yves Pidoux (City of Lausanne), Dr. Christian Zurbrügg (Eawag: Swiss Federal Institute of Aquatic Science and Technology), and Dr. Jon-Andri Lys (KFPE) for their highly appreciated involvement and support.

Likewise, this project could not have succeeded without the quality and diversity of the contributions of the various authors and researchers. In response to the call for papers, the Scientific Committee evaluated over 140 papers and ultimately selected 125 to be presented at the Conference. Of these, 15 were finally chosen based on the following criteria: (1) Innovative concept and research questions versus an extension of existing work; (2) Originality of the methodology including North–South, South–South partnership; (3) Contribution to the discipline as whole and; (4) Clarity and understandability. We express our appreciation to all these authors, without whom this publication would not have been possible.

In addition, we would like to very warmly thank Mr. Emmanuel Estoppey and Ms. Jeanne Corthay from the Lavaux UNESCO World Heritage Site who went out of their way to welcome us for the social event. All of the Conference participants greatly appreciated the opportunity to spend some time outside the conference halls and to experience the splendor of the Lavaux Vineyards.

Our sincere thanks also go to the team from Ingénieurs du Monde (IDM) and our colleagues at CODEV who contributed extensively to the organization of this conference.

Finally, we are very grateful for the generous patronage of the Swiss Agency for Development and Cooperation (SDC), the Canton de Vaud, the City of Lausanne, the Swiss National Science Foundation (SNSF), Cleantech Alps and the KFPE—Commission for Research Partnership with Developing Countries, the conference sponsors. Their support and their partnership is critical to the achievement of our common mission which is to identify innovative solutions that are able to reduce poverty and lead the way toward more sustainable development at a global level.

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Part I
Introduction

Chapter 1
Technologies for Development: What Really Matters?

Silvia Hostettler

Abstract Technological innovation is vital for finding solutions to key challenges the world is facing. Climate change, pollution, disease, rising inequalities, and chronic poverty all need to be addressed. We need renewable energy sources, efficient transport networks, functioning public health systems, well-designed infrastructure, improved agricultural systems, and access to quality education for everyone. Technologies for development play a key role as pathways to sustainable development. Developing and emerging countries can take advantage of technological leapfrogging in key domains such as health (mHealth), energy (solar, wind, and hydropower), education (massive open online courses [MOOCs]), urban development (smart cities), and agriculture (precision farming). Developing and emerging countries could even surpass high-income countries in the use of information and communication technology (ICTs). We can expect technological innovation to be increasingly developed in the Global South and to become a source of inspiration for the Global North. Living labs, open-source, and open innovation movements are growing trends that will support and accelerate the development of effective technologies. Standards are needed to guarantee the quality, reliability, and safety of technologies in the Global South, particularly for medical devices. International Standards Organization (ISO) and United States Food and Drug Administration (FDA) standards often prove to be slow, inaccessible, and expensive.

1.1 Introduction

The EPFL-UNESCO Conference on Technologies for Development (2014 Tech4Dev) focused on the question, "What is Essential?" Indeed, in a world in which we are permanently connected and bombarded with a wealth of information,

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S. Hostettler et al. (eds.), *Technologies for Development*,
DOI 10.1007/978-3-319-16247-8_1

there is undeniably a need to find out what is important and to set priorities. This is particularly true in the field of development in which so many challenges persist. How can we effectively reduce poverty? What is the role of technologies? How can they be successfully developed and deployed? How can their impact best be evaluated? We know that technologies must be developed in partnership with the intended beneficiaries and ideally in a local environment to be compatible with the socioeconomic and technological context (Hostettler and Bolay 2014). We also know that we have to integrate potential up-scaling from the beginning of technological development. This will allow us to manufacture a technology at a large scale at affordable cost once we have developed an appropriate prototype.

Successful technological innovation will depend on all these factors. However, in this introduction I wish to take a step back and focus on the question "What really matters?" It seems that what we need are technologies that support sustainable development in its social, environmental, economic, cultural, and political dimension. We need technologies that are energy efficient, accessible to all, and environmentally and financially sustainable in the long term.

1.2 Key Challenges

If we look at the world, we realize that we face very important developmental challenges indeed: unsustainable lifestyles, production and consumption patterns, the impact of population growth and climate change, to name just a few. Even though some significant progress has been made since 1990, 15 % of the global population still live in extreme poverty and 805 million people are still chronically undernourished (FAO et al. 2014). At the same time, roughly 30 % of all adults in the world are overweight (Sachs 2014). The global population continues to grow and is expected to reach nine billion in 2040 (UN DESA 2013). The demand for resources will rise dramatically. "*By 2030, the world will need at least 50 % more food, 45 % more energy and 30 % more water—all at a time when environmental boundaries are throwing up new limits to supply*" (United Nations 2012, p. 11). Clearly, the current global development model focused on short-term economic profit is unsustainable. We will need to make a consistent effort to find solutions to these challenges. Technological innovation is one pathway to sustainable development.

The potential of technologies for development has been particularly well illustrated by the technological leapfrogging that occurred in countries like Singapore, South Korea, Hong Kong, and Taiwan. These Asian governments realized the central role of technological innovation for development, and they started promoting research and development programs (Rowen et al. 2007). The Asian tigers were able to take over large parts of the technology industry between 1960 and 1990 and invested increased national income into education, health, and public transportation systems, thereby raising the standard of living for the entire population. However, the question of the sustainable use of resources and the pollution linked to technological progress needs to be part of the equation. Technological progress needs to come from sustainable technologies (Sachs 2014). These technologies may, for instance, focus on energy efficiency in smart cities to using information technology for a range of applications from mHealth to precision farming. One key challenge is to achieve sustainability in the environmental, social, and economic sense. It is not sufficient if a technology is financially sustainable in the long term but its production is based on extensive use of fossil fuels or on social exploitation. In the same way, a technology that is appropriate but unaffordable will equally fail. An encouraging example is the Fairphone which is not only a technology that can potentially contribute to development by improving access to information, health and financial services, but is also produced by a social enterprise that aims to develop a smart phone with minimal harm to people and the planet. This brings us to yet another problem, a problem of scale. At what spatial and temporal scale do we measure sustainability?

The concept of planetary boundaries has emerged to define a "*safe operating space for humanity*" as a precondition for sustainable development. The nine planetary boundaries were first introduced in 2009 and apply to climate change, change in biosphere integrity, ocean acidification, stratospheric ozone depletion, biochemical flows, land system change, freshwater use, atmospheric aerosol loading, and introduction of novel entities (Steffen et al. 2015). The framework identified and quantified these planetary boundaries within which humanity can continue to develop for generations to come. Scientific research indicates that human actions have become the main driver behind global environmental change since the Industrial Revolution. The framework asserts that once human activity has passed certain thresholds defined as "planetary boundaries," there is a high risk of "*irreversible and abrupt environmental change*" (United Nations 2012). Four of these nine planetary boundaries have now been crossed, according to a group of 18 international scientists, driving the world into a much less hospitable state. Altering these "core boundaries" will most likely lead to a deterioration of human well-being in many parts of the world, including high-income countries (Steffen et al. 2015).

1.3 Technological Leapfrogging

What is clear is the preponderant role technologies will play in our efforts to identify pathways to sustainable development. Some technologies will allow emerging and developing countries to technologically leapfrog ahead in certain domains. This has already happened in the field of telecommunications. On average 75 % of the world population own a mobile phone (World Bank n.d.). Many countries will not install fixed telephone lines in all regions. A large part of the population moves directly to the stage of owning and using mobile phones and smart phones which opens enormous possibilities. For instance, the percentage of mobile cellular subscription users in Bolivia jumped from 71 in 2010 to 98 in 2014 (World Bank n.d.). Many countries are "skipping" the initial step and leveraging the development of cheaper, more advanced technology. This is particularly true for the domains of health (mobile health), education (distance learning), and energy (solar, wind, and hydropower). Developing countries have the opportunity to technologically leapfrog to renewable energy solutions, thereby avoiding as much as possible dependence on fossil fuels. Seeing rapid urban development, emerging countries in particular should seize the opportunity to build smart cities wherever possible in these often resource-poor contexts. Developing and emerging countries could even surpass high-income countries in the use of information and communication technologies (ICTs) (Howitt et al. 2012).

What matters in the field of technologies for development is that the technology contributes to sustainable development and is in itself as sustainable as possible in terms of use of valuable resources, its contribution to pollution, and the social issues linked to its production. We can simply not afford to continue in a direction driven mainly by financial motives.

Although healthcare systems in low-income countries often lack the most fundamental drugs and devices, the potential of technological leapfrogging needs to be further explored. We need technologies that provide healthcare services to the largest possible number of people, technologies that increase energy efficiency, technologies that allow access to knowledge and information, technologies that increase food production and food storage. We need low-carbon energy infrastructure technologies that support the construction of adequate infrastructure with low CO_2 emissions.

However, before embarking on developing a technology, we should ask ourselves a few key questions: Will this technology help the world to remain within the planetary boundaries? Is it sustainable in the social, economic, environmental, cultural, and political dimensions? Is it safe? Are local stakeholders in the partnership, especially governments, willing to support it in the long term? Will it contribute to poverty reduction either directly or indirectly (improve health, increase access to education, create employment)? Does the technology contribute to endogenous development because the benefits will also remain as much as possible local? Will this technology be appropriate and affordable? Is the technology just the "next new thing," or will it have a lasting and maintained development impact?

We also need a financial system that supports the development of adequate technologies. We need social impact funding that supports social entrepreneurs as outlined in Chap. 2 by Jennifer Brant. We need trade reforms and changes in many national subsidy policies that will give developing and emerging markets the chance to catch up. We need proper development finance systems. We need continued financial support for low- and middle-income countries, specifically in the form of targeted aid programs in the public health sector, at least until a country has acquired the ability to finance a well-functioning health system independently. This is still a major challenge for many countries. In a low-income country such as Malawi, the annual income per capita amounts to only US$400. With a 20 % tax level, the income for the government per capita in taxes is US$80 annually (Sachs 2014). With these funds the government is supposed to cover the costs of government administration, legal courts, educational systems, infrastructure, roads, power supply, and the public health system. Even if the total tax revenue was available for health, with US$80, the government cannot even cover the costs of an effective public health system with appropriate clinics and trained health staff, much less finance all the other development needs of the country. Knowing how crucial the health of a population is for a country's development, there is evidently a continued need for external support. By way of comparison, the public health budget in Europe and the United States amounts to US$3000 and US$4000 per person per year, respectively (Sachs 2014). In the long term, Zach Friedman and Walter Karlen (Chap. 11) argue that a multidisciplinary dialogue and public–private partnerships are essential to the integrity and success of low-cost health systems in small and fragmented markets.

And then there will always be challenges that cannot be resolved through technology. Most importantly, we need a redefinition of what quality of life and social inclusion mean. We need a set of values and ethics based on the knowledge that the world's resources are finite and a conviction that everyone has the right to a decent life.

The needs appear overwhelming at times, but the potentials are equally staggering. There is much cause for hope if we look at the tremendous development impact technologies can have as the papers of this publication illustrate. Consider only the case of mobile phones: They are able to increase access to health services (Chap. 6 by Balaji Parthasarathy et al.), facilitate financial services such as remittances (Chap. 5 by David M. Garrity) and enable farmers in Burkina Faso to conduct precision farming that saves irrigation water and increases food production (Chap. 3 by Clémence Ranquet Bouleau et al.). Mobile health using mobile communication technologies offers encouraging avenues for providing healthcare services to low-income countries. As trained personnel and infrastructure are often rare in developing countries, an mHealth solution can for instance consist in the implementation of antenatal care to improve the health of mothers and newborns via text messages. Smart phones even allow diagnosis via embedded biomedical sensors and phone-based diagnostic kits (Chap. 15 by Nicole Leeds et al.).

Another technology that is opening up new horizons is 3D printing. 3D printing of medical devices (see case study on Haiti by A. Dara Dotz in Chap. 4) can address immediate needs such as supplying umbilical cord clamps and oxygen splitters. This technology can potentially decrease the dependence of hospitals on commercial companies located in the Global North. Devices can be printed locally on demand and in the quantities needed at any time. 3D printing enables the production of individually tailored prosthetic arms, legs, and other human organs in an environment with limited resources. Although the initial investment in 3D printing technology is relatively high, costs of 3D printed medical devices quickly become much cheaper than if they were purchased from a company in the Global North. The sustainability of this technology can even be increased by using portable solar printers as has been done in Haiti.

Considering technological innovations in the Global South, what matters most at the end of the day is that they have a real impact. Therefore, being able to obtain data on the performance and impact of a developed technology is crucial. Emerging technologies such as wireless sensors and remote sensing techniques are opening new possibilities for measuring the impact of technological innovations. For instance, sensors on bioprosthetic arms can measure the time the arm is actually being worn, which allows accurate feedback for adapting the design and increasing the usefulness to the intended beneficiaries. D-Rev produces a prosthetic knee (Chap. 14 by Samuel Hamner et al.) and shares collected data on impact assessment publically, thereby increasing efficacy, transparency, and accountability. Ashok J. Gadgil and Temina Madon (Chap. 16) provide an overview of three different ways to measure the impact of development innovations. First, impact can be measured through sensors that capture the active use of improved cookstoves in Sudan (see Chap. 20 by Daniel L. Wilson et al.). Second, electronic data from mobile phones or mobile banking can be used to analyze the use of these technologies related to specific events such as epidemics. Third, field trials (e.g., randomized controlled trials) are used to estimate the social impacts of the adoption of new technologies. Carefully considering the ethics of using sensors and personal data must be an integral part of impact measurement.

Sachiko Hirosue et al. (Chap. 7) show how innovation is increasingly occurring in emerging and developing countries. The Global South can be expected to take a leading role in innovatively using technologies for development and become a source of inspiration for the Global North. This trend will be reinforced by emergent practices around open access, open data, open science, and open-source hardware[1] that will support practicing science that is more critical and inclusive and therefore finally more successful. The study on rural sanitation in Bangladesh by F. Conor Riggs and Chetan Kaanadka (Chap. 10) illustrates the advantages for commercial firms to adopt an open innovation business model as opposed to the traditional closed innovation approach. This allows them to generate a “living lab”[2] environment that accelerates the development of an appropriate product that is rapidly up-scalable. A positive feedback loop can be created by this “living lab business model.” Finally, Kate Michi Ettinger (Chap. 8) argues that an open-source quality, reliability, and safety (QRS) system could foster healthcare innovations that are safe and gain easier access to markets in low- and middle-income countries. An open-source approach would allow pooling limited resources and would support the construction of a solid, transnational QRS system as an alternative to the costly and lengthy processes used by the International Standards Organization (ISO) or the United States Food and Drug Administration (FDA) which might become obstacles to innovation themselves.

[1]Open-source hardware is “hardware whose design is made publicly available so that anyone can study, modify, distribute, make, and sell the design or hardware based on that design” (see Chap. 7 by Sachiko Hirosue et al.).

[2]The European Network of Living Labs describes a living lab as “an open innovation environment in real-life settings in which user-driven innovation is the cocreation process for new services, products, and societal infrastructures” (www.openlivinglabs.eu).

1.4 Conclusion

Let us come back to the original question: What really matters? Being aware of the fundamental challenges the world faces today, training future engineers in multi-disciplinary problem-solving will be decisive for addressing the world's most pressing problems. This means focusing not only on the technological challenge but also taking into account the larger socioeconomic, environmental, and cultural context. A new interdisciplinary field is taking root in North America, driven by the University of California, Berkeley and associated academic institutions such as Massachusetts Institute of Technology (MIT). *Development Engineering* integrates engineering with economics and business, energy and natural resource development, and social sciences (Nilsson et al. 2014). This is a significant move in the right direction which is furthermore supported by the launch of a new peer-reviewed journal—*Development Engineering*—in 2015. It will offer a discussion and knowledge exchange platform for a wider audience of development practitioners and policy makers, with evidence that can be used to improve decision-making.

Ultimately, technological innovation must contribute to sustainable development at the global level. Technologies will be an important part of solutions that will allow humanity to develop while remaining within the planet's safe operating limits. This will imply finding new solutions in the fields of health, energy, transport, infrastructure, sanitation, food production, climate change, and many others. It will also imply stabilizing the world population by improving health conditions and access to quality education. Technological innovations such as massive open online courses (MOOCs) and mHealth contain significant leapfrogging potential because they are linked to other key development challenges. The sustainability of the technology itself also matters substantially. It should be produced with minimal impact on the environment and under fair socioeconomic conditions. Decision support tools such as the Technology Applicability Framework (described in Chap. 18 by André Olschewski and Vincent Casey) centered around 18 sustainability indicators need to be further developed and promoted, ideally in an open-source environment. The United Nations Millennium and Sustainable Development Goals can help focus the direction of technological innovations on specific, measurable, and consolidated goals. Finally, the question of standards matters. What kind of standards can be developed that are appropriate for technological innovations that need to be safe, reliable, affordable, and meet the needs of the beneficiaries living in resource-limited settings? These are some of the issues we will further explore at the next EPFL-UNESCO Conference on Technologies for Development (2016 Tech4Dev) during May 2–4, 2016.

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Part II
Innovative Technologies for Development

Chapter 2
Commercial Channels for Sustainable Technology Deployment in Developing Countries

Jennifer Brant

Abstract Technological advancement is instrumental to enhancing productivity, generating economic growth, and improving peoples' lives. "Technology diffusion" is the dynamic process by which new solutions are developed and deployed, adapted, and improved upon. Among the many approaches to stimulating technological innovation and diffusion, the most effective integrate knowledge held by different actors with complementary expertise. Partnership is a powerful driver of innovation and can help to ensure that new solutions effectively address user needs, thus enhancing the sustainability of technology deployment. In light of this, commercial models for technology innovation and diffusion increasingly involve collaborative, "open" innovation. Commercial approaches to technology diffusion are most effective when an enabling policy environment is in place. This paper reviews enabling policies and other factors that support partnership, innovation, and global technology diffusion involving commercial entities. The analysis is based on presentations at the 2014 EPFL-UNESCO Conference on Technologies for Development (2014 Tech4Dev) by four experts on commercial approaches to technology diffusion.

2.1 Introduction

The deployment of new technologies can accelerate improvements in social and economic welfare in developing and developed countries alike. A key factor in enhancing productivity, generating growth, and improving lives, technological advancement plays an important role in development.

New technology offers solutions to critical challenges where none existed previously, as well as new solutions that are more cost-effective. New technology can improve the ability of governments to address pressing public policy challenges,

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S. Hostettler et al. (eds.), *Technologies for Development*,
DOI 10.1007/978-3-319-16247-8_2

while enabling people to enjoy longer, more comfortable lives. Moreover, the process by which technology is developed, deployed, adapted to local needs, and improved upon involves a dynamic process of learning that enhances the local knowledge base and improves the innovative capacity of all involved. Made up of individual technology transfer transactions over time, the process by which technology and knowledge flow and are absorbed locally can be called "technology diffusion."

Speakers at the 2014 EPFL-UNESCO Conference on Technologies for Development (2014 Tech4Dev) highlighted a range of models for the development and diffusion of innovative technology solutions for users in developing countries. Approaches grounded in charity, community initiatives, public–private partnerships, regional and national government initiatives, commercial transactions, and other approaches were discussed. Irrespective of the particular approach adopted, many speakers agreed on: the need to accurately identify and effectively respond to the needs of technology users; the value of cost-effectiveness as a characteristic of new solutions; and the need for creative business models that can support not only the development of new solutions but also their sustained deployment where most needed.

Commercial models provide one sustainable approach to global technology innovation and diffusion. In this context, "sustainable" means self-sustaining over time, from a financial perspective or in the sense that knowledge is being transferred so as to enable local partners to continue working with and improving upon the technology. With their high growth rates, need for massive infrastructure investments in coming years, and sizeable and growing customer base, it is no surprise that increasing attention and resources are being directed at needs in developing countries. Global firms consider that sustainable technology innovation for and deployment in these markets will require the right business and policy environments.

Enabling environments that stimulate and reward investments in research and development (R&D) and that support collaborative innovation can accelerate technological advancement in developing countries. An enabling business environment develops over time, the result of actions by both private and public actors. It includes: investments in education and training (which enhance local "absorptive capacity"); investments in infrastructure; macroeconomic stability; a sound financial system, including access to finance for entrepreneurs; the existence of networks for knowledge creation, such as universities and research centers; functioning courts and rule of law; and the provision of public services such as intellectual property (IP) protection. While not sufficient on its own to drive development, the right policy and business environment can support entrepreneurship while attracting investments and technology partnering, contributing to job creation and a better local innovative capacity.

Partnership is most likely to thrive in an environment with the above elements. Collaboration, also known as "open innovation," is a crucial channel through which technology and know-how flow globally. Collaborative innovation is rapidly becoming the premier innovation model as firms are driven to partner with a range of entities—including universities, NGOs, government agencies, and other firms—with complementary knowledge and skills, wherever they may be located. Collaborative innovation models, in concert with globalization and advances in information and communication technology (ICT), have opened up new opportunities for entities in developing countries to participate in global innovation networks.

A collaborative innovation model enables firms to better manage risks associated with product development and commercialization, in an era of rising product complexity, competition, and R&D costs. It is underpinned by trust and supported by IP protection and other laws. IP systems are particularly important for partnerships in that they provide recourse if one partner uses proprietary knowledge shared by the other as part of their collaboration without authorization or in a dishonest manner. In places with an effective IP system, firms are generally more willing to share their most valuable technology and know-how.

Companies engaging in global technology transfer, that is, any firm collaborating and commercializing solutions across countries, regularly point to partnership with local actors as critical to successful technology deployment. By working with local partners, foreign firms can gain the knowledge necessary to successfully adapt their offerings to local needs. This can ensure that, once deployed, solutions are used and maintained properly, and that customer feedback is integrated into future R&D. Local partners benefit from the foreign firms' technical knowledge and know-how.

The following additional observations can be made about commercial channels for sustainable technology innovation and diffusion in relation to developing country markets.

Cost-effective innovations are not necessarily simple. Many people have heard about "frugal innovation," which is the development of low-cost, low-tech solutions for users in developing countries. But they may not be aware that complex solutions are also valued by customers in developing countries, as they can provide the same or greater cost savings as simple inventions. For instance, General Electric has developed a prefabricated production module for biopharmaceuticals that is aimed at developing country markets (Mages 2014). The KUbio results in production that is, on average, 30 % cheaper than a traditional facility built from the ground up. This saves the customer, whether a government agency or firm, money over the life of the technology. Value for money is also important for customers in developed countries, and solutions originally intended for developing country users often find commercial success in mature markets.

Sustainability requires developing offerings that users are willing to pay for. Firms know this well: if a solution is not useful or appropriately adapted to the context in which it will be used, customers will not materialize and the business will not thrive. In other words, to be convinced to part with their money, customers must derive real value from an innovation. This was the case with a project run by a public–private consortium, working under the Qualcomm Wireless Reach initiative (Tronchon 2014). The consortium provided South African nurses with innovative 3G-connected mobile libraries. After an evaluation determined that this technology enabled nurses to better serve patients, particularly in remote areas, the regional health authorities began the process of mainstreaming the technology into health services delivery. Because the solution had effectively solved a healthcare challenge, the government considered it to be worth paying for.

Developing an appropriate, desirable technology solution is not enough. There must also be a business strategy that can effectively get the technology to where it can actually be used. Simpa Networks, a green energy company based in India, has been open about how difficult it can be to turn green electricity users into paying customers (Needham 2014). Simpa's innovation is not the solar energy systems that its partners install for customers, but rather the Simpa pay-as-you-go business model for the provision of green energy, notably the innovative hardware/software system that supports it. Creative conditions in new markets, for instance collaboration with unconventional partners, for instance firms working with nongovernmental organizations (NGOs), may be needed to sustainably get solutions to those who can benefit from them.

Knowledge exchange is important to ensuring that a solution truly solves a problem. Partnerships with local actors can help firms to adapt their offerings to meet real needs and conditions in new markets, for instance those relating to customers at the bottom of the pyramid (Parthasarathy 2015, Chap. 6). Within partnerships, knowledge flows in multiple directions. Foreign firms supply technical solutions as well as knowledge and training, a process that over time contributes to the local knowledge base and improves local innovative capacity. In return, outside firms benefit from local market knowledge and opportunities to explore new ideas with partners.

Cost-effective innovation often entails using existing tools in new, efficient ways. Innovation may be a question of discovering new ways to use tools that are already accessible to people to deliver services and meet their needs more cost-effectively. Cell phones provide an example of a ubiquitous tool that can be leveraged and combined with new tools, such as new applications, to improve productivity and support the effective delivery of public services.

Social entrepreneurs' impact is diminished when they cannot secure adequate finance. The 2014 Tech4Dev conference featured presentations by a range of startups that were formed to address important social challenges in innovative ways. These "social enterprises" will need funds to demonstrate their concept, build the business, and grow and scale. Although recognized as important actors in innovation, startups often find it challenging to secure the resources they need to launch. Social entrepreneurs face particular difficulties. They must often rely on their own resources to get started, and they face a dearth of funding until they can create a track record of success that can enable them to attract traditional investors. "Development finance" systems, targeted specifically at the needs of social entrepreneurs, could help.

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Chapter 3
Low-Cost Wireless Sensor Networks for Dryland Irrigation Agriculture in Burkina Faso

Clémence Ranquet Bouleau, Theo Baracchini, Guillermo Barrenetxea, Alexandre Repetti and Jean-Claude Bolay

Abstract Dryland irrigation is a major concern in arid and semiarid regions where agricultural output is low and water a scarce and vital resource. Irrigation efficiency and sustainability are, therefore, of paramount importance in these regions, where small farmers generally over-irrigate vegetables to avoid yield loss, resulting in excessive water consumption, unnecessary water pumping costs, and soil degradation. Improving dryland irrigation support requires field data, which is often scarce and unreliable in developing countries, being mostly collected manually with obsolete equipment. Modern automatic weather stations are costly, and local resources for station repair and maintenance are limited. The research project Info4Dourou2.0 aims to improve environmental data collection in developing countries by using low-cost wireless sensors networks (WSN). Hydrometeorological stations have been designed specifically for harsh environmental conditions and the limited local resources. They are simple to install and require little maintenance. The collected data is available in real time via a mobile phone and a web interface. These completely automatic stations have been developed by Ecole Polytechnique Fédérale de Lausanne (EPFL) and the start-up sensorscope, with the aim of being manufactured, assembled, maintained, and commercialized locally. Results of the present study show that by coupling autonomous and continuous measurements of meteorological variables with soil-water-plant-atmosphere models, we have

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S. Hostettler et al. (eds.), *Technologies for Development*,
DOI 10.1007/978-3-319-16247-8_3

designed a simple irrigation management system that has a strong potential to improve agricultural production: up to a 38 % yield increase has been achieved using 20 % less water compared to the unassisted way of irrigating.

3.1 Introduction and Purpose

Dryland irrigation is a major concern in arid and semiarid regions, where agricultural output is low and water a scarce and vital resource. Irrigation efficiency and sustainability are, therefore, of paramount importance in these regions, where small farmers generally over-irrigate vegetables to avoid yield loss, resulting in excessive water consumption, unnecessary water pumping costs, and soil degradation.

Improving dryland irrigation support in these arid and semiarid regions requires field data. However, essential environmental data in developing countries is scarce and unreliable, being mostly collected manually with obsolete equipment. Modern automatic weather stations are costly, and local resources for station repair and maintenance are limited. Collecting hydrometeorological data is nevertheless particularly crucial in this context, where current changes in climate conditions significantly affect agricultural activities.

The research project Info4Dourou2.0 first aims to improve environmental data collection in developing countries by using low-cost wireless sensor networks (WSN). Hydrometeorological stations have been designed specifically for harsh environmental conditions and the limited local resources. They are simple to install and require little maintenance. Using wireless technologies, stations facilitate information access by making collected data available in real time via a mobile phone and a web interface. These completely automatic stations, developed by the Ecole Polytechnique Fédérale de Lausanne (EPFL) and the start-up sensorscope, have been tested in Burkina Faso over several years. A local engineer is in charge of installation and maintenance so that the stations may be manufactured, assembled, maintained, and commercialized locally.

Info4Dourou2.0 is, therefore, oriented toward two applications: environmental data collection for national weather services and dryland irrigation support. Collecting relevant and reliable hydrometeorological data is critical for better understanding of climate change in the Sahel regions. Low-cost automatic weather stations using WSN significantly increase the amount of data collected and, consequently, improve meteorological model accuracy and predictions (Barrenetxea et al. 2008).

Hydrological data collection also plays an important role in dryland irrigation where water management is fundamental for achieving sustainability. By combining local measurements with soil-water-plant-atmosphere models, which are recognized as powerful tools for the management of water resources at multiple scales (Ioslovich and Gutman 2001; Simoni et al. 2011), we propose an irrigation support system that will improve the efficiency of water allocated to the plant by providing information on the specific needs of the crops, depending on their stage of growth and on the water available in the soil.

3.2 Design and Methods

3.2.1 Low-Cost Wireless Sensor Networks

The Info4Dourou project started in 2008 with the objective of providing a flexible turnkey sensing system to study environmental parameters in semiarid regions. During the first phase of the project, we developed low-cost meteorological stations specifically designed for the harsh environmental conditions of these regions. Drawing on the wireless network research conducted at EPFL (Ingelrest et al. 2010), the measurement system is based on multiple sensing stations that self-organize into a multi-hop wireless network and work as a distributed measurement system. Thanks to its ability to produce high-density spatiotemporal measures, this system has been used in multiple environmental applications, where spatially distributed data is needed. Designed with the aim of being produced, maintained, and commercialized locally and with limited resources, stations are simple to install and require little maintenance. The system was tested over three years in Tambarga, Burkina Faso (Mande et al. 2014). As in all semiarid regions, the activities of Tambarga, a small village surrounded by national parks in the landlocked country of Burkina Faso, are subject to the seasonality of the local hydrology. Seasonal and spatial variability of rainfall shapes the livelihood of rural farmers, which consists mainly of rain-fed agriculture. We instrumented the Tambarga catchment to study the hydrologic processes including surface runoff formation, base flow, evaporation, and land cover controls on the local water balance. We used a network of wireless sensors to assess the hydrologic importance of vegetation in the Sudanian Savannah and to understand the hydrologic consequences of land conversion, which is essential for developing land-use practices that conserve ecosystem function.

The measuring stations consist of a small main plastic module powered through four AA rechargeable batteries and a solar panel embedded inside the main box, no external batteries being required (Fig. 3.1). All electronic devices are safely embedded inside the main box, protected from the harsh environmental conditions: dust, heat, direct sun, insects, and heavy rains that can occur during the wet season. Three sensors directly connected to the main box measure multiple atmospheric and soil-related parameters, like soil moisture and temperature. The data are measured every two minutes and, if required, sent to a base station via a radio module embedded in the main box. The base station collects the data from all the stations in the network and sends the data every 15 min to a database using a mobile connection (Fig. 3.2).

Fig. 3.1 Wireless sensing stations

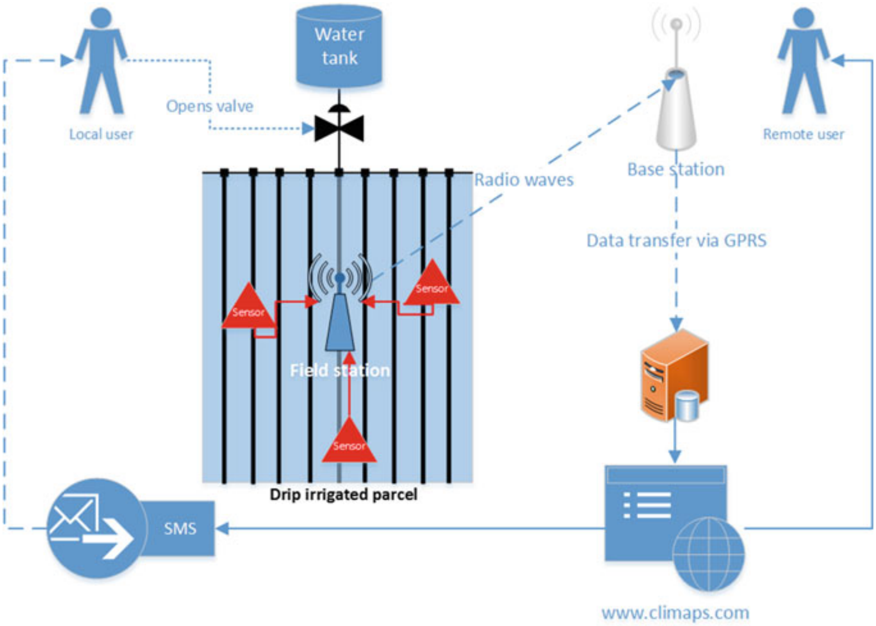

Fig. 3.2 Data collection for local and remote users

Stations communicate wirelessly and self-organize into a wireless sensor network capable of transmitting information using a multi-hop routing protocol. Particularly, stations implement a data gathering communication protocol that collects all the sensing measurements collected by the stations into a single base station. Using a synchronized duty cycling radio protocol that minimizes radio usage, overall energy consumption is significantly reduced. We designed a lightweight routing protocol that randomly selects the next hops from the neighboring stations closest to the base station, making the whole routing protocol robust and dynamically adaptive to environmental changes.

The data collected by the base station is made locally available through simple interfaces [Light-emitting diodes (LED)] and openly available through a web application (www.climaps.com), providing remote users with reliable and real-time data.

3.2.2 Water Management System

Drip irrigation systems are currently being installed in semiarid countries to increase food security, revenues, and self-reliance. These drip irrigation systems are affordable, and payback is quick in view of the reported water savings and yield increases (Chigerwe et al. 2004). Water management remains a fundamental aspect of irrigation success. However, farmers have difficulties in evaluating water needs and generally over-irrigate or under-irrigate, which leads to excessive water consumption, unnecessary water pumping costs, and, consequently, to the reduction of the irrigated surfaces, and, in turn, significant productivity loss. This water management issue concerns all irrigation techniques: gravity flows from reservoirs, watering can irrigation from groundwater wells, and micro-irrigation or drip irrigation.

We designed an irrigation management system to optimize yield and water consumption in irrigated agriculture through the use of communication and sensing technologies. It is based on soil matrix potential continuous measurements coupled with a simple agronomic model. The system informs the farmers through a simple interface of the correct amount of water needed by the plant. When the soil matrix potential drops below a defined threshold in the roots area, a light on the station turns red, and/or a text message (SMS) is sent to the producer on his cell phone, thereby providing the right information at the right moment to mitigate and/or preclude water stress to the plants.

The sensors used for the experiment are watermark sensors by Irrometer, (n.d.), with a granular matrix sensor that measures the soil-water matrix potential. It is composed of electrodes measuring the resistivity surrounded by a fine granular matrix enveloped in a permeable membrane. The resistance is measured in Ohms, and a calibrated function from the manufacturer delivers the soil water potential (AEC System, n.d.).

3.2.3 Model

The irrigation management system we propose combines continuous soil-water matrix potential measurements with an agronomic model to provide simple irrigation instructions to the farmer. The main objective of the model is to determine the timing and quantity of water the crop needs depending on the stage of growth and on the water already available in the vicinity of the roots. The agronomic model also provides optimal sensor locations for the measurement of the soil-water content.

Drip irrigation is based on fixed irrigation schedules defined as short but frequent irrigation periods. This approach does not take into account local parameters such as the variation of daily evapotranspiration or the precise soil texture. Another common approach consists of relying on the farmer's experience, triggering irrigation based on visual or physical estimation of the soil state. Both methods result in suboptimal water usage and productivity (Jones 2004).

Given the configuration of drip irrigation systems and to facilitate the information delivered to the farmer, we implemented a simple irrigation scheduler based on the soil potential measurements that indicates when irrigation is needed through a simple LED indicator and an SMS. Our system takes into account local environmental parameters as well as daily variations of evapotranspiration. Our main goal is to trigger irrigation just before plants experience water stress (Mermoud et al. 2005), in order to maximize the transpiration of the plant and consequently its yield. Thresholds for irrigation depend on the plant, its sensitivity to water stress and, most importantly, its growth stage.

To determine the soil-water dynamics, optimal thresholds, and sensor locations, the modeling environment HYDRUS-2D (Simunek et al. 1999) has been used. HYDRUS-2D allows the simulation of water, heat, and solute movements in two-dimensional unsaturated mediums. It can assess root water uptake and water stress, as well as propose irrigation schedules.

Reference evapotranspiration values have been computed separately at a 15-minute time step based on local environmental data provided by the sensorscope meteorological stations. Among other attributes, temperature, radiation, wind speed, and humidity data have been used to compute the Penman-Monteith equation proposed by the FAO (Allen et al. 1998). This reference evapotranspiration was then used with the dual crop coefficient from the FAO (Allen et al. 1998) in order to derive evaporation and transpiration rates used as input by HYDRUS-2D.

Optimization was facilitated, allowing a maximal difference of 5 % between the actual and potential plant transpiration over a 1.6 m portion of a spray boom. Four growth stages have been considered, in accordance with the data and studies provided by the FAO (Brouwer and Heibloem 1986) for each culture, in order to account for the different water sensitivities over the lifecycle of the plant and root development. This approach provided us with a theoretical irrigation schedule and, most importantly, optimal soil potential thresholds and sensors' locations.

3.2.4 Experiment

The system was tested during 14 different campaigns starting from the 2012 dry season to the present day. The campaigns assessed seven different drip irrigated cultures in seven locations. Two villages are located in the north of the country, 30 km north of Ouahigouya, in the Sahel region of Burkina Faso. Four other locations are in the vicinity of the capital, Ouagadougou, a Sudano-Sahelian region in the center, while the last one is a village 100 km west from the capital.

This pilot experiment was implemented using a participatory approach with all stakeholders, and a convention was signed with the various farmers' associations to set up the conditions for the experiment.

The drip irrigation allowed for accurate monitoring of the quantity of water allocated to the plant. Irrigation areas were equipped with measuring devices, each with two different parcels:

- An experimental parcel, where the producers used the device and followed the irrigation advice given by the system through a simple red or blue light system, or through the receipt of an SMS on their mobile phone when the crop needed water.
- A control parcel used as a reference, where measurements were taken but no advice was given.

Generally, one water tank of 3 m^3 was used to irrigate 500 m^2, via two Netafim drip kit systems (Netafim, n.d.) of 250 m^2 each. However, in some cases other setups were considered. Every sensor was placed at a depth of 12 cm in the soil for onion cultures (shallow root zone) and at 17 cm for other cultures, in order to be as close to the root system as possible.

The thresholds of the sensors were first set based on the literature data (Thompson et al. 2007) combined with visual appreciation of the soil state and plants' water needs, and then on modeling of the water dynamics. This experiment was designed as a pilot experiment, so optimization of these thresholds is still ongoing for future testing due to new modeling techniques. Finally, the thresholds vary in time in order to meet the crop water needs that evolve as they grow.

For each successful campaign, water consumption and weight of harvests of each system tested were measured.

3.3 Results

3.3.1 Experimental Results

Among the 14 campaigns performed in Burkina Faso, only the results of 7 are presented here. This is because three campaigns are still ongoing today; therefore, no harvest data is available yet, and six were subject to failure. Indeed, diseases,

Table 3.1 Results of the pilot experiment

Location	System type	Beginning/End of campaign	Culture	Water used (m^3)	Biomass (kg)	Water efficiency (kg/m^3)
Koubri	Experiment	14.04.2014	Gombo	177	961	**5.43**
	Control	26.08.2014		183	913.5	4.99
Koumbri	Control	23.12.2012	Onion	180	244	1.36
	Exp. light only	07.04.2013		143	336	**2.35**
Koumbri	Control	21.06.2013	Chili-Pepper	502	1278.75	2.55
	Experiment	20.04.2014		428	1405.98	**3.29**
Nariou	Experiment	05.01.2014	Onion	95	511	**5.38**
	Control	02.04.2014		88	401	4.57
Zom	Control	24.12.2012	Onion	112	193	1.72
	Exp. light only	07.04.2013		118	269	**2.28**
AMIFOB (Ouaga)	Experiment	20.06.2014	Gombo	188	169.2	**0.90**
	Control	27.10.2014		225	172	0.76
IDE (Ouaga)	Experiment	05.09.2014	Zucchini	43	1173	**27.28**
	Control	14.11.2014		53	1216	22.94

High efficiencies in bold

drought, ignorance of irrigation schedules, misfit thresholds, destruction by animals, technical failures, and human mistakes (valves left open, sensors flooded by children playing, etc.) are all unpredictable factors that contributed to the degradation of the data and unreliable results.

Table 3.1 presents the water consumption and weight of harvests for each system tested.

The results in Table 3.1 obtained with this pilot experiment show that a higher yield could be obtained with limited water availability. Particularly, in Koumbri for the onion culture, a yield increase of up to 38 % was obtained using 20 % less water with the system using the light signal, in comparison with the control system where no advice was given to the producer. Figure 3.3 and Table 3.1 show that whether it is in terms of water saving or harvest gains, this assisted irrigation system has always been beneficial for the producers.

The median water consumption efficiency is higher (around −15 % water consumption) where advice has been given to the producers than with the control parcel, suggesting that the water has been allocated to the plant in a more efficient way, and that this resource has been more efficiently utilized, resulting in less waste. Figure 3.4 suggests that those water savings have not been achieved at the cost of a smaller harvest, as a median increase of 10 % is obtained.

Indeed, except for the experimental system of the onion production, water savings were always significant. However, although 5 % more water was consumed in this case compared to the control setup, the biomass production was 38 % higher. Important water savings were obtained with the zucchini culture, reaching −19 % at the cost of a reduction of 3.4 % in production.

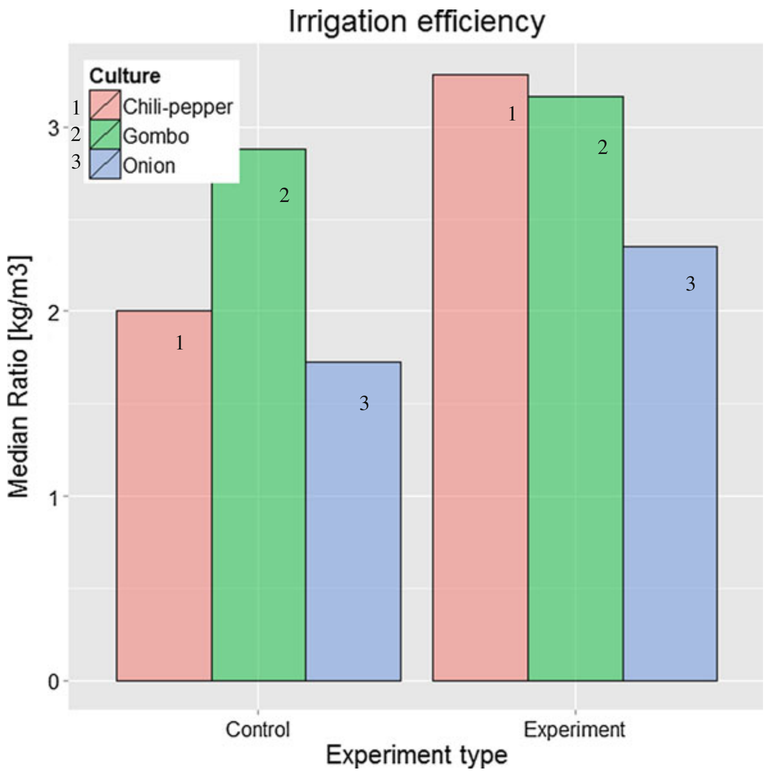

Fig. 3.3 Control and experimental setup efficiency for three different cultures

Although the light-only system is easier to implement and provided good results farmers particularly appreciated the use of SMS to receive the information. In fact, they were able to focus on other living activities while attending their fields, allowing them to earn more money. The light-only system was therefore discontinued in most of the recent experiments.

In every successful campaign, results show that this sensor based irrigation method allows for higher yields with limited water use and for improved food security in comparison to the traditional drip irrigation system.

In arid and semiarid countries, most of the year is subject to a period of drought with little to no precipitation, making the use of an irrigation system of paramount importance. Nevertheless, during the rainy season precipitation levels are uneven and some areas are subject to short periods of drought that have a negative impact on yields, sometimes even leading to complete loss of crops. This can be avoided using this irrigation management system, which is why the stations were tested during the rainy season as well.

In order to achieve sustainability, this pilot experiment was voluntarily led directly in the field using a participatory approach with the producers in order to

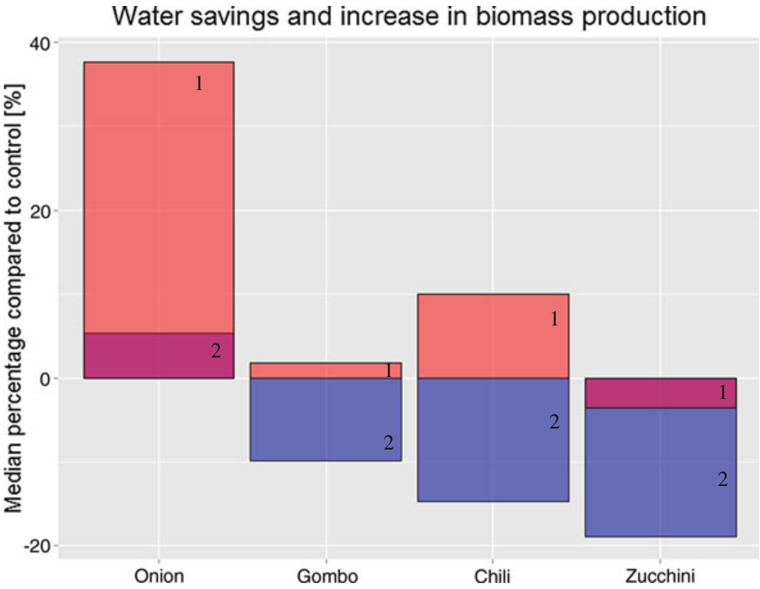

Fig. 3.4 Increase in biomass production (*1*) and water savings (*2*) for the different cultures and systems

develop the proper technology with the direct beneficiaries themselves. This led to inevitable protocol approximations on the field, so that the results presented above are to be considered as preliminary results. Although very promising, they are still to be consolidated throughout wider experiments.

3.3.2 Modeling Results

Water movements and root water uptake have been simulated to acquire better understanding of the water dynamics in a local soil type with two vegetable cultures (onion and eggplant). As a first step, we built a HYDRUS-2D model based on existing field measurements acquired at various locations in Burkina Faso. The simulations were validated by monitoring and comparing measured and modeled soil matrix potential. As a second step, optimal irrigation threshold, sensors location, soil type, and plant types (root distribution and sensitivity to stress) were assessed.

Our simulation domain consists of a simple 2D vertical rectangular domain (Fig. 3.5). Water stress is simulated using the Feddes water stress response function. In particular, it defines a threshold below which roots cannot extract water at maximum rate, and those thresholds depend on the growth stage of the plant. Indeed, the literature from the FAO (Brouwer and Heibloem 1986) states that the

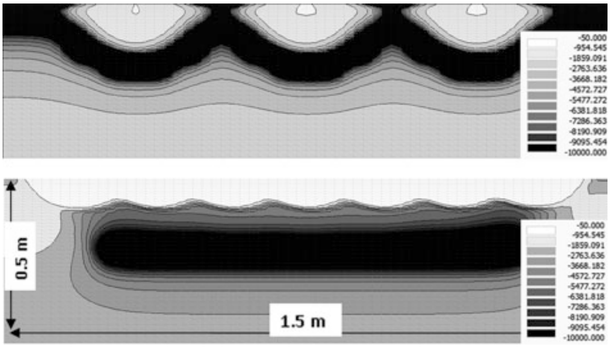

Fig. 3.5 2D section along a spray boom with three drippers. Eggplant model up (three plants, deeper roots), and onion model down (uniform and shallower root zone). Shading represents the pressure head (mm)

crop is most sensitive to water deficit during the yield formation period, particularly during the period of rapid bulb growth, which occurs about 60 days after transplanting. To achieve large bulb size and high bulb weight, water deficits, especially during the yield formation period (bulb enlargement), should be avoided (Steduto et al. 2012). The lowest thresholds were, therefore, identified during this period. Due to limited water supply, small water savings can be made during the vegetative period and the ripening period. Finally, it is assumed that water uptake is maximal at the top of the root zone with a linear decrease until their end.

The results show that optimal sensor depths are located between 5 and 10 cm, which are above the 12 and 17 cm currently considered. Indeed the soil matrix potential below 10 cm is not representative of the whole root zone, especially at early growth stage which leads to suboptimal root water uptake in the upper root zone.

Figure 3.5 shows the pressure head for two different cultures after an irrigation event. It seems clear that for deep root structures (>0.4 m), the water is not able to reach the bottom part of the root structure, leading to yield losses. Practically, this will constrain the development of the roots to develop at a more shallow level, leading to a higher sensitivity to environmental conditions of the plant as water in the upper part of the soil is more sensitive to high evaporation rates under high-temperature events. Higher irrigation doses at lower frequencies are therefore suggested.

3.4 Perspectives

By creating a realistic model, we were able to define adequate depths and thresholds for soil matrix potential sensors for optimal irrigation control. Although the results obtained in this pilot experiment differ slightly from this theoretical approach, several suggestions can be made to improve the results, such as lower sensor depths and increased irrigation doses.

Root distribution is a critical parameter for simulation and is subject to significant uncertainties. To obtain more accurate results, maximal root depth, radius, and biomass distribution will be assessed by field measurements. Transpiration values will be measured in the field, as well as soil granulometry and composition, different sensor depths, location and thresholds, various irrigation doses, etc. Every measurement will be performed at different growth stages for several cultures. Moreover, more experiments, in close collaboration with the drip irrigation promoters in the country, are planned in 2015 across Burkina Faso in order to strengthen the results obtained.

3.5 Conclusion

Low-cost wireless sensor networks have strong potential to improve agricultural production. Project Info4Dourou2.0 has been leading pilot experiments in the field since 2012, showing that hydrometeorological stations facilitate significant water savings while increasing production and, therefore, food security: in some cases, producers in Burkina Faso have achieved up to 38 % yield increase using 20 % less water compared to the non-assisted way of irrigating. Additional experiments will allow for more solid results, corroborating the previous results or bringing new inputs to the research program, leading to a wider use of this irrigation management system in semiarid and arid countries to improve food security.

A participatory approach with stakeholders and beneficiaries along with close collaboration with all water management partners in Burkina Faso are key factors for the development of appropriate technologies and to achieve sustainability. A local company will be in charge of manufacturing and commercializing the stations in Burkina Faso to allow for long-term appropriation of the technology.

These reliable low-cost automatic hydrometeorological stations will effectively contribute to sustainable management of groundwater resources, a decisive issue for developing countries in arid and semiarid areas, where most of the year is subject to a period of drought with little to no precipitation, making the use of irrigation systems of paramount importance.

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Chapter 4
A Pilot of 3D Printing of Medical Devices in Haiti

A. Dara Dotz

Abstract 3D printers are small-scale manufacturing facilities in a box. With minimal resources, they enable rapid on-demand production. Cost-effective complex products are made when needed with decreased transportation, storage, and customs costs. The immediate access to medical devices created by 3D printing reduces uncertainty and delivery delays. This paper introduces a pilot project to collaborate with local clinicians and design medical devices with a 3D printer in Haiti. The pilot aimed to empirically ascertain whether locally engaged staff could implement 3D printing of medical devices. This process may be replicated globally and brought to other areas of need. On multiple occasions, we visited three healthcare delivery sites in Haiti. By observing and interviewing medical staff, we identified high-demand supplies with the potential for 3D printed fabrication. We also identified equipments not used due to broken parts that could be easily fabricated. In collaboration with local clinicians, we developed a list of 16 3D printable objects to meet the localized demand in real time. 3DPforHealth launched a 3D printing lab in Haiti and trained local people in design using the Makerbot Rep 1 printers. To demonstrate 3D printing medical application, we collaboratively designed an umbilical cord clamp prototype. Variants of the clamp design were iteratively tested to assure durability and efficacy of grip on multiple materials. The process identified initial concerns of printing medical devices including sanitation, product longevity, reuse of retired materials for new product development, and parameters for responsible human trials. Initial trials demonstrate proof of concept for identification and 3D printed production of much-needed medical devices by collaborating with local clinicians. Further, we were able to train local people in 3D printing design. In recent months, 3DPforHealth has been absorbed into a larger initiative for disaster response manufacturing known as Field Ready (http://www.fieldready.org). We envision Field Ready as a replicable model for countries struggling with similar challenges. Field Ready is now a program that designs solutions that are shared with other resource-constrained environments, bypassing infrastructure and distribution limitations globally.

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S. Hostettler et al. (eds.), *Technologies for Development*,
DOI 10.1007/978-3-319-16247-8_4

4.1 Introduction and Purpose

The catastrophic Haitian earthquake of 2010 resulted in a death toll estimated to be between 200,000 and 500,000 (Sloand et al. 2013). Providing critical medical care in the desperately short window of time proved to be one of the greatest challenges during the disaster. Injuries and casualties continued even after the initial quake due to the rubble and unsafe terrain (Smith et al. 2012).

Local medical staff shared stories of what they deemed in-humane treatment in moments of crisis. In order to save lives from gangrene and other infection, they were forced to perform amputations using only a bread knife and vodka to disinfect the wound when they ran out of appropriate medical supplies. It is in these critical moments that clean sanitary medical devices are most needed.

During a disaster, there is a crucial 48-h period after a wound is inflicted where proper medical supplies are needed to stop the spread of infections and preventable deaths. Though some supplies were air dropped, much of it could not reach the people who needed it most. Between January 12 and May 31, 2010, Médecins Sans Frontières (MSF), one of the many humanitarian organizations on-the-ground, provided emergency medical care to more than 173,000 patients (MSF 2014). The earthquake destroyed 60 % of the existing health facilities and 10 % of medical staff were either killed or left the country (MSF 2011).

Conflicting reports of death tolls mean that no one knows the true-life cost of the devastation. The country as a whole is still reeling from its effects. Regardless of the numbers, the same question rings: What could be done to prevent this?

Aid to Haiti was overwhelming following the earthquake in January 2010. Since 2010, funding has been greatly reduced and lasting change for the better has not been achieved (Rupar et al. 2013). Poverty, the lack of resources and adequate infrastructure are the greatest challenges facing Haiti. The persisting need for healthcare resources, lack of access, and limitations of the distribution systems in this disaster-stricken country contributes to a steadily increasing toll of preventable deaths.

The current state of Haiti illustrates that while the doors are wide open for collaboration between North and South partners, they are yet to be explored fully. This presents an opportunity for collaborative design initiatives and exponential growth technologies. With the majority of its people living on less than US$2 per day (Buss 2008), very few Haitians can afford healthcare, making it difficult to support small local economies specializing in specialty medical equipment and services.

The great need for health care resources and lack of access to them highlights the challenges and limitations of the distribution systems in this disaster-stricken country. Sustainable design and innovation along with exponential growth technologies can combine to answer the critical questions of “What could be done to prevent this?” and “Why is this still happening?”

Our efforts are dedicated to the belief that the answers lie in our basic assumptions of how proper access to medical care can be acquired. If we can help clinicians gain access to the proper equipment quicker, cheaper, and easier, we have the potential to, on the whole, save thousands of lives daily in disaster-struck areas. Being able to manufacture simple medical devices on-demand when needed has tremendous value for the treatment of patients. Not only will the immediacy of device production save lives but also storage, contamination, and theft risks can be avoided.

By empowering locals to design and create their own tools (through capacity building), we empower them to have an even stronger impact on the lives of those around them. The goal is to create and distribute or share the model of a 3D printing lab that can print much-needed medical devices on-demand. In this lab, we (North) teach local (South) clinicians how to rapidly prototype and produce tools via hyper local digital manufacturing, in particular, small, simple, medical devices that have tremendous value in the immediacy of need. We also aim to eliminate storage risk by reducing waste and contamination. Eventually, we would like to create a system that can be shared and copied freely with other areas providing a sharing model from South to South, not just the typical North to South model.

4.2 The Need for Technology

There is no denying the great need for medical devices in resource-limited environments such as Haiti. Current limitations facing this pilot program are funding, material resources, lack of technical training, and lack of sufficient infrastructure to access such materials. Every day 800 women die worldwide due to complications with pregnancy and childbirth. Almost 50 % of all the countries surveyed by the World Health Organization (WHO) have less than half the essential medicines needed for basic healthcare in the public sector (GHO 2013). There is a clear calling for this technology with so many in need.

Currently, the Disaster Aid model is to deploy people with general tool kits, as they do not know what they are going to specifically need on the ground. The kits are also dependent on replenishment of supplies, which depends on donors, infrastructure, transport capabilities, and safety of environment. Further, the traditional method of getting aid is a slow and cumbersome method, which can waste materials, money, and time (Chu et al. 2011). The process may involve risk elements in regards to collection of donations, purchasing parts, international shipping, customs, and storage. The latter two adding much time to the process in terms of delays caused by infrastructure and bureaucratic inefficiency (Lancet 2010).

After the earthquake, airports were clogged often with too much congestion by competing nongovernmental organizations (NGOs) deploying unnecessary items (Krin et al. 2010). No one could get through, literally stopping the aid that was on the ground ready to deploy. By using a general-purpose material like plastic in the form of filament that could be made into a variety of tools and supplies, there is a chance this would alleviate some of the issues outlined above.

The scope of this project is greater than just disaster areas and we would like to apply the project to positively benefit limited resource clinics and environments in general. Clinics such as Ti Kay, a TB/HIV clinic, are a perfect example of a rural clinic that is based in a post-disaster zone with limited resources. Based on the grounds of the general hospital in Port-au-Prince, Ti Kay is extremely resource challenged and miraculously serves the poorest of the poor with dignity and respect. Collecting no money from patients, it survives solely on the donations of others. We are working directly with the Ti Kay clinic and they graciously participated in the pilot project.

We, Field Ready[1] (which absorbed 3DPforHealth) are developing a platform that can be replicated globally and brought to other areas of need by sharing the designs of tools, customization, and simple fixes on machinery. The platform will share and address solutions that have environmental similarities (such as humidity) by sharing freely online. Locally engaged staff, from clinics in Haiti, will be able to share their experiences with staff based in other countries; and a platform will be facilitated for them to do so.

4.3 Design and Methods

3DPforHealth launched its pilot in Port-au-Prince, Haiti. The location was chosen for its stark healthcare needs, access to medical clinics and professionals, and safe base of operations to operate our machines and design classes. The urban setting promoted a safe environment for teachers, clinicians, and local staff to engage, develop, and learn. The project was based in an established community resource center, Haiti Communitere (North and South), a nongovernmental organization (NGO) focused on response, relief, and renewal. It was established within days of the earthquake.

Partnerships between North and South are critical for the implementation and success of this project. We have done this by piloting in an innovation lab, known as iLab/Haiti, which was founded in a partnership with KIDmob (North). iLab/Haiti is an innovation lab which teaches local Haitian clinicians and unskilled locals (residents of Cité Soleil) creative problem solving skills, design skills, maker skills, and empathy building. While Field Ready focuses on disaster response, KIDmob is dedicated to teaching and developing general curriculum for design.

Over the course of a year, we visited a number of healthcare sites in Haiti. At each site, we observed and interviewed doctors and nurses to identify needs for supplies with the potential to be made with a 3D printer. In addition to basic supplies, we also noticed the number of complex medical devices present but unused because of broken parts. Minor pieces easily produced on a 3D printer are able to restore functionality to this equipment. Some repairs required very simple items in the proper size, like screwdrivers and wrenches. These were easily created during our trials demonstrating that the technology can be used to create any number of useful tools and rehabilitate previously valued devices that had fallen into disrepair.

[1]http://www.fieldready.org.

We worked with a variety of medical stakeholders; local nurses, clinicians, and local residents based in the different areas of Haiti:

- Ms. Maeve McGoldrick, a disaster response nurse who worked in Haiti juggling clinics in these areas; Ti bois, Williamson and Fond Baptiste in Haiti;
- Dr. Coffee, Harvard and MIT Infectious Disease specialist at Ti Kay, a TB/HIV clinic;
- Dr. Julielynn Wong consulting doctor for NASA with experience in 3D printing medical tools for astronauts;
- Five (formally) uneducated young men from Cité Soleil.

We codeveloped new iterations with local clinicians (South), and tested on a variety of materials and quality with medical professionals (North). We also researched a range of highly effective and more importantly simple medical devices that would have the highest impact.

The advantage of working with clinicians on the ground learning and developing solutions mutually is that we in the North can now provide access and expertise to those in the South so they can codesign or design themselves what is "actually" needed and what is culturally appropriate for their medical needs. We (North) simply do not know, nor can we, the exact needs of the Haitians as they do.

The rural hospitals we worked with identified umbilical cord clamps as a key need. They did so as many births occurred directly after the earthquake, brought on by stress (Blencowe et al. 2010), and clinicians were forced to use shoelaces as umbilical clamps; which presented a contamination risk (UNICEF 2014). After they finished using their shoelaces, they switched to clipping off and using the fingers of their sanitary gloves; which amplified the safety risk for the clinicians as many of the women giving birth were potentially HIV/AIDS positive. The women and children were also at significant risk since umbilical (Ibrahim 2008) cord hemorrhaging (resulting in anemia/death) can also occur if the umbilical cord clamp does not properly occlude one or more of the umbilical vessels (partial clamping of the cord) (Garner et al. 1994).

We designed a prototype of an umbilical cord clamp to demonstrate the concept that 3D printers could be used for localized, on-demand medical device manufacturing. We iteratively designed clamp prototypes to assure their durability and tested the effectiveness of the clamp's grip on multiple materials. With 58,000 infant deaths in 2010 worldwide due to neonatal tetanus (UNICEF 2014), one can see the tremendous beneficial effect of dissemination and application of this 3D printing lab approach.

4.4 Results

After establishing partnerships with clinics, 3DPforHealth found that it was possible to design and work side by side with local clinicians to identify and create solutions to address the lack of much-needed medical supplies. 3DPforHealth was

Table 4.1 Medical devices

Bandage clips	Stop cock (tuberculosis)	Knives
Scalpel	IV bag hooks	IV bag hangers
Physical therapy tools	Urine sample cups and lids	Pill boxes
Umbilical cord cutter	Irrigation syringe	Fluid and O_2 valves
Silicone adapter pieces	Umbilical cord clamp	Oxygen splitters

then able to work with local clinicians iterating and codesigning medical devices with success. 3DPforHealth has identified a list of 15 medical devices thus far (Table 4.1) which we are confident can be produced with 3D printers. We are focusing on three currently, identified as the most in need by our clinician partners: umbilical cord clamps, oxygen splitters, and IV bag hooks. We found that one of the most important devices needed in the Tuberculosis (Farmer et al. 1991) clinic, Ti Kay, was an oxygen splitter, which we were able to create and test.

IV bag hooks, oxygen splitters, and umbilical cord clamps have been identified and prototypes have been produced with success utilizing a dual extruder Makerbot Replicator 1 in Port-au-Prince, Haiti. This printer was functional, affordable, and suited to the environment due to its durability and ease of repair. Furthermore, as printers become more common a secondary market of used printers has started to emerge.

Some initial barriers to entry may be that initial projected costs may be high for the local clinician, as in Haiti, it may cost too much for a local Haitian in a small clinic to afford. Over time, we believe the 3D printing lab will become more affordable or can be supplied by external aid organizations in the form of a donation. Much depends on how quickly we can move forward and on how much time or how frequently our team can work onsite in our 3D printing labs.

Costs of small-scale 3D printers are dropping drastically. When printers were first released to the public, the machines cost hundreds of thousands of dollars. A decade later, they are accessible to the layman in the western world for some US$499–8,500 with a printing resolution of up to 100 μ. Not only are prices decreasing for commercially available 3D printers, but also people all over the world are creating their own open-source-based printers in new, innovative, and affordable ways.

> Kodjo Afate Gnikou, a resourceful inventor from Togo in West Africa, has made a US$100 3D printer which he constructed from parts he scrounged from broken scanners, computers, printers and other e-waste. The fully functional Do It Yourself (DIY) printer cost a fraction of those currently on the market, and saves environmentally damaging waste from reaching landfill site (Popsci 2014).

The technology is becoming more and more affordable to the developing world. With the costs of a filament recycler recently dropping to US$400, it is possible to utilize all scraps and prints gone wrong allowing for a higher degree of efficiency. It implies a range of simple devices, between 500 and 1000 devices, could be produced from one kilo of Acrylonitrile Butadiene Styrene (ABS) plastic as opposed to the traditional 100–300. Further, it is not unrealistic to assume that if we incorporate recycling of used devices, we could produce 2000 simple devices from one kilo of ABS plastic, without degradation of the material (Kickstarter 2013).

We identified initial limitations of printing medical devices on a 3D printer, including concerns about how to sanitize the clamps, when to retire the product, how to reuse the materials of retired clamps for new product development, and how to responsibly test these devices on humans. This pilot is ongoing and staff has been back and forth to Haiti numerous times since January 2013, exploring the options and capabilities available.

To set up a successful 3D printing lab, community engagement is critical. We learned that our expectations should be flexible, as it took longer than anticipated to set up a functioning lab in a new environment. We imagine that it will be even more challenging without having established relationships and trust built before entering the environment. A significant amount of one-on-one time in the early stages is required to ensure that the local participants understand, as translation can be complicated particularly with complex concepts. It can take up to a month to get someone back in the lab to work if holidays are around, or if danger is prevalent, which is quite common in Haiti. To give an example, a number of our locally engaged staff encountered violence in the area during 2013 that directly arrested their participation in design class. We expect the process will become more streamlined as we apply the project to more areas in need.

As with any learned skill, 3D printing can be taught. It is a technical aptitude and some are quicker to adopt the skill set than others. We believe that with the help of a flexible and translatable curriculum, a good deal can be accomplished. In collaboration with local clinicians, we developed a list of 15 objects that can be made with a 3D printer to meet the localized demand in real time. We also successfully trained local people to design in 3D, using the Makerbot 3D printers. We learned the process of designing a medical device on a 3D printer collaboratively with locally engaged staff.

We believe it is viable to create a self-sustaining design lab based on 3D printing technologies, but it will take time to get it off the ground. In the future, it will be more streamlined. Setting up the labs will be much easier after all research has been completed alongside user experience materials, such as pictorial directions and a premade suggested kit (3D printer and other tools) is established with an initial investment amount. This will also include a recycler so that materials may be reused lowering the cost of production even further, and reducing waste along the way.

As detailed in Table 4.2, one of the most interesting results of this project is the comparable price to traditional methods and in some cases an extreme reduction of cost. To achieve the same economies of scale with traditional clamps (sans shipping/customs/storage) 10,000 pieces must be ordered at one time. This makes 3D printing a much more affordable alternative as a rural clinic is unlikely to need 10,000 clamps in any short horizon of time, nor is it likely to have the space needed to store 10,000 clamps securely.

With the potential of recycling and a dual nozzle extruder, one can further cut down on costs. Recycling is yet to be fully proven out, but if the project can include

Table 4.2 Pricing

Dual extrusion: makerbot replicator 1	US$	2200.00
Includes x2 kilos of ABS; includes US shipping pax 200		
5 kilos of ABS including shipping pax 500	US$	200.00
Luggage fees	US$	50.00
Cost per piece	US$	3.50
Recycler x3 use	US$	400.00
Cost per piece		1.36
XYZ printing inc: 3D printer	US$	499.00
Cost per piece		1.07
XYZ printing inc: 3D printer with recycler	US$	499.00
Cost per piece	US$	0.36
Briggs double grip umbilical cord clamp inc. shipping pax 125	US$	236.09
Shipping to Haiti	US$	100.00
Cost per piece	US$	2.69
Medline umbilical cord clamps inc. shipping pax 100	US$	51.59
Shipping to Haiti	US$	100.00
Cost per piece	US$	1.52

Sources Amazon online shopping, medline (medical distributors)
Assumptions: printer is carried by volunteer to location, software is free open source (Autodesk 123); location has power four hours a day; laptop supplied; while prices are cheaper for higher quantity of shipping, it is untenable to ship large volumes to small rural clinics

this technology on the basic 3D printing lab, we will be able to collect used (as well as broken or worn down) medical devices, sterilize them, grind them down to be recycled, and used to create new devices. The advantage of having a dual nozzle extruder on the printer provides the ability to print two different types of plastic simultaneously: external material with raw virgin ABS and the internal core support out of recycled plastic to ensure durability of the device.

For the purposes of this project, it appears that ABS filament is the superior filament option as it is the sturdiest and most dependable material we can easily access. It also has the advantage that it can be recycled. The aim is to further test how many times one can recycle the filament, which would ideally lead to a closed loop system for medical devices.

After one of the umbilical cord clamps have been used, they can be sanitized, ground up, recycled, and be reused and reprinted an unknown amount of times. After two uses, the cost of the 3D printer filament already pays for itself. It is unknown how many times the plastic can be recycled, but it is safe to say that it can be done at least two to three times without any serious degradation of the plastic.

We believe that our 3D printing lab will be easy to transport with volunteers carrying 3D printers and filament in their travel luggage as opposed to shipping them in. Filament packages are so small that as volunteers cycle through an aid project, more can be brought in luggage without having a significant impact on their luggage dimensions and weight. To get materials into Haiti we have tested a system to address low material supply by having volunteers carry a kilo of ABS with them each time they enter the country. In this manner, we have a steady stream of supplies coming in. Boards on 3D printers can fail and replacements are hard to come by; to address this issue, we have volunteers bring extra parts and used back up machines.

Access to electricity is problematic and without a dependable power source, we are not able to guarantee any short-term result for medical devices needed. This is a key concern to consider in the design of this project.

We also need to consider the risks arising from the proper sterilization of tools as we could encounter cross contamination that could then lead to illness. Once we have set the process for sterilization, which we are currently investigating alongside our clinician partners, and created user experience materials to provide a pathway for learning there are still risks with people not following directions or taking shortcuts. This is where legal and quality assurance built into the process is key. We are going to build into the design a method that allows users to know when the tool or device is past its prime as well as ample warning that they must follow all directions explicitly.

One item that is not fully addressed in this paper, and is still under study for is device patents. At this point, we do not consider patent infringement to be an issue as none of these parts are being sold, and further, the majority of designs will be designed independently of existing patents via collaboration of North South partners. Some items will be completely redesigned for more appropriate functionality for the need at hand. This will be an ongoing area of study to ensure that we mitigate legal risk for the project.

We anticipate that designs must be tested and tweaked repeatedly in a variety of environments: social, geographical, and climate. Designs must be quality assessed on the development end and we will need to requality test devices in each location due to a variety of factors: heat, humidity, skill level of clinician, quality of printer, and the final quality of print. We are looking into how to create a sufficient feedback loop now. We have done experimenting on this front that are currently in trials; for example, with the umbilical cord clamps, mothers must return the clamp as payment for a secondary check up on the infant.

Another small hindrance may be the time to manufacture for complicated pieces. This can sometimes take up to an hour and a half and constant power is required for a stable print. Finally, because most 3D printers are deployed in the developed world where access to reliable power is not an issue, there is a stark lack of research in this area. We intend to publish our results to improve the knowledge base of the international aid community.

Power access is a big hindrance and we may need access to a high-quality generator to ensure continuous power, as well as a Uninterrupted Power Supply (UPS), to handle momentary lapses of power so as not to disturb the 3D printer as it prints. We are currently in the process of investigating the possibility of using a specialty solar kit and battery to power the 3D printers. Many options will become more available as prices lower and dependability increases. We view durability as the key issue here as we do not want to create a 3D printing lab that will break down easily or require replacement parts frequently.

The ethical and health impact of testing on humans in this area is currently unclear. While patients may require a medical device, we do not intend nor will we, deploy a medical device which has the potential to cause harm. We are also extremely mindful to consider after care. Finding patients to test on (once we ascertain there are no health risks) will be critical to success but we have to be cautious of intentional or unintentional coercion. Currently, the clinician asks the patient for their consent, and the patient may accept or decline; keeping in mind that the patient may fear not receiving health care if they do not go along with the experiment.

We are also working on preventing theft. Our experiences show that by making sure our local team feels valued and important, we can reduce the loss of equipment through theft. We are also sensitive about power dynamics particularly amongst foreigners and locals. Some of these dynamics may not be obvious. We have found that our locally engaged teams provide insights that are invaluable in terms of designing great local solutions, and while they may not realize it, we try to help them understand their capabilities and strengths.

4.5 Conclusions

Our ongoing pilot project continues to demonstrate that it is possible to collaborate with local clinicians to identify requirements for much-needed medical devices which can be made with a 3D printer. Further, we were able to meet the goal of training local people to design with 3D printers. Field Ready has been founded in part to develop and deploy an easily replicable model for other countries struggling with similar challenges. We will be a site that can design solutions to be shared with other resource-constrained environments, bypassing infrastructure and distribution limitations.

We are also confident that our model will work in other locations in the future; however, this will require much study to see how the model can be applied with partners globally. We are working to illustrate the Haiti use case and further develop our open source “Disaster Tool Kit.” We are working to establish a feedback loop, where devices, Frequently Asked Questions (FAQs), and curriculum can be shared and updated with ease; so that all parties can benefit from the learning achieved. We believe that this method will allow locals on the ground to save lives with medical device production, rather than being limited to dependence on the few formally trained aid workers in the area that have access to traditionally sourced devices and supplies.

We also intend to work with other professionals to gain their expertise and advice. Made in Space is exploring 3D printing capabilities on the International Space Station (ISS); and will be launching as early as summer 2014. Their user case is quite similar to ours given the resource deprived nature of their situation; astronauts are going to use 3D printers to print replacement parts and tools when needed without having to wait for the next rocket launch. If the ISS is in need of a fix that they simply cannot solve themselves, they can now reach out to a network of other experts and engineers on the ground to create a solution who will email them the fix. This is similar to what we are trying to achieve with our project in Haiti.

We intend to study the lifetime of devices and recycling capabilities, other devices that may be useful in clinics, and other printing materials we can use. We are also going to research which medical devices are being produced locally so we do not compete with local industry; to prevent the oft-made mistake of out competing local production and shutting down local industry.

This approach also pushes parts and designs to new limits enabling novel medical capabilities to arise locally. Material innovations will provide new areas of exploration. For example, in the near future, we intend to print O-rings and custom silicone fittings of a variety of different sizes as needed. We also aim to create a downloadable catalogue of devices and parts. When a lab needs a specifically sized tool, part, or device in a disaster scenario, there will be a large variety to choose from as the basis for customization. Taken together, there is also an added benefit where a larger variety of materials, designs, and machines can be used to replace parts and convert or modify previously donated pieces, regardless of manufacturer, into valuable capabilities.

We believe that 3D printers represent a major technological sidestep to traditional manufacturing methods and infrastructure restrictions, similar to that of mobile phones over traditional copper wire networks. When the power of the Internet, computers, and 3D printers are put to use, the North and South can finally share a new healthier and innovative future.

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Chapter 5
Mobile Financial Services in Disaster Relief: Modeling Sustainability

David M. Garrity

Abstract Mobile Financial Services (MFS) have provided marginal populations with access to basic financial services, including savings programs and insurance policies. Disaster relief response has been characterized by the use of MFS as a vehicle for charitable donations, both directly from diaspora populations as well as campaigns organized by traditional relief organizations. The paper will develop a financial model and analysis of how scaling MFS can be commercially viable and sustainable. The analysis will assess the extent to which the deployment of MFS as a disaster risk mitigation measure may be enhanced by the provision of information on available risk profiles. The paper will assess the enabling environment for successful deployment of MFS as a mechanism for managing financial shocks in disaster relief and for mitigating individual risk. Statistical models have been developed using mobile network operator (MNO) call detail records (CDRs) to assess which subscribers may present better credit risks as well as how to best structure premium levels and payment methods to best fit subscribers' abilities and needs. Based on such models and on the pricing structures of MFS, the paper will extrapolate from instances where farmers have secured insurance against weather-related crop failures and where MFS have been developed. MFS adoption in developing countries follows a model in which remittances lead to the adoption of other MFS. The overview indicates that the existence of established reciprocity and social networks drives volume and that establishment of trusted networks is critical to MFS achieving scale. In conclusion, the analysis will examine how patterns of use of MFS provide an informational basis on which disaster risk reduction can be implemented in different form factors.

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S. Hostettler et al. (eds.), *Technologies for Development*,
DOI 10.1007/978-3-319-16247-8_5

5.1 Mobile Financial Services in Disaster Relief: Modeling Sustainability

The powerful role of information and communication technologies (ICT) in disaster relief has become one of tech in development's success stories. The use of SMS messaging in early warning systems and in crisis mapping has been well documented elsewhere (West and Valentini 2013). Most notable here is the speed with which elements of each subsequent disaster relief deployment are analyzed and adapted, an alacrity fueled in part by the extent to which climate change is accelerating the incidence of severe weather events. Recent disaster relief response has also been characterized by the use of mobile financial services (MFS) as a vehicle for charitable donations, both directly from diaspora populations as well as campaigns organized by traditional relief organizations. The paper develops a financial model and analyzes the institutional circumstances under which scaling MFS is commercially viable and sustainable (Duncombe 2012). The analysis will assess the extent to which MFS deployment as a disaster risk mitigation measure may be enhanced by providing information on available risk profiles and examine the potential sustainability of mobile micro-insurance (MMI) as a means of mitigating disaster's impact on population. The model will focus primarily on Sub-Saharan Africa.

5.2 Mobile Financial Services

In Sub-Saharan Africa, in particular, the potential of mobile ICT and MFS to have development impact has been assessed through myriad market-related deployments. Several instances of text-to-market prices have been implemented in the region, usually with donor support for the initial piloting stage (Aker and Mbiti 2010). The use of ICT in such search functions, reducing information, and time costs has been the focus of research on increased market efficiencies, with an emphasis on agricultural markets (Aker and Mbiti 2010).

MFS have provided marginal populations with access to basic financial services (e.g., money transfer). Within Sub-Saharan Africa, the expansion of MFS, particularly in respect to the enabling regulatory environment for the m-Pesa take-off, has been the subject of analysis by development practitioners and private sector scrutiny from the banking community and mobile network operators (MNOs). Meanwhile, mobile subscriber growth in other countries has outpaced that of Kenya, thus providing the necessary platform for MFS expansion elsewhere. Similarly, the use of mobile money for remittances has grown (even after the impact of anti-money laundering (AML) limitations). The patterns of sending and receiving are captured in Fig. 5.1. Overall, global remittance flows total US $550 billion and are growing approximately 10 % annually (CGAP 2013).

Sent from/ Received by	Total US$	IN US$	CN US$	MX US$	PH US$	NG US$	EG US$	PK US$	BD US$	Other US$
US	120.16	10.84	13.45	23.17	10.04	6.13	0.61	0.96	0.59	54.37
SA	24.19	7.62	0.00	0.00	2.65	0.33	3.96	2.60	1.33	5.70
CA	23.40	3.15	4.03	0.11	1.92	0.46	0.21	0.47	0.14	12.92
UK	23.16	3.90	0.74	0.01	0.61	3.88	0.12	1.34	0.74	11.83
DE	21.74	0.41	0.92	0.03	0.19	0.61	0.09	0.14	0.03	19.31
FR	19.99	0.21	0.63	0.01	0.04	0.07	0.12	0.62	0.01	18.28
AE	18.22	14.26	0.00	0.00	0.70	0.00	0.65	1.49	0.40	0.71
AU	14.63	1.25	2.15	0.01	0.81	0.09	0.18	0.07	0.07	10.03
RU	11.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11.44
JP	11.09	0.12	4.44	0.00	1.08	0.07	0.01	0.03	0.04	5.31
Other	219.57	21.26	35.01	0.24	4.96	8.99	8.38	4.54	8.72	127.47
Total	**507.60**	**63.01**	**61.37**	**23.59**	**23.00**	**20.62**	**14.32**	**12.26**	**12.07**	**277.36**

Share of Total	Total	IN	CN	MX	PH	NG	EG	PK	BD	Other
US	24%	2%	3%	5%	2%	1%	0%	0%	0%	11%
SA	5%	2%	0%	0%	1%	0%	1%	1%	0%	1%
CA	5%	1%	1%	0%	0%	0%	0%	0%	0%	3%
UK	5%	1%	0%	0%	0%	1%	0%	0%	0%	2%
DE	4%	0%	0%	0%	0%	0%	0%	0%	0%	4%
FR	4%	0%	0%	0%	0%	0%	0%	0%	0%	4%
AE	4%	3%	0%	0%	0%	0%	0%	0%	0%	0%
AU	3%	0%	0%	0%	0%	0%	0%	0%	0%	2%
RU	2%	0%	0%	0%	0%	0%	0%	0%	0%	2%
JP	2%	0%	1%	0%	0%	0%	0%	0%	0%	1%
Other	43%	4%	7%	0%	1%	2%	2%	1%	2%	25%
Total	**100%**	**12%**	**12%**	**5%**	**5%**	**4%**	**3%**	**2%**	**2%**	**55%**

Top 10 Recipient of Migrant Remittances and Share of Total		
India (IN)	US$ 63.01	12%
China (CN)	US$ 61.37	12%
Mexico (MX)	US$ 23.59	5%
Philippines (PH)	US$ 23.00	5%
Nigeria (NG)	US$ 20.62	4%
France (FR)	US$ 19.48	4%
Egypt (EG)	US$ 14.32	3%
Germany (DE)	US$ 13.39	3%
Pakistan (PK)	US$ 12.26	2%
Bangladesh (BD)	US$ 12.07	2%
Total	**US$ 263.11**	**52%**

Top 10 Recipient of Migrant Remittances as a Share of GDP	
Tajikistan (TJ)	47%
Liberia (LR)	31%
Kyrgyzstan (KG)	29%
Lesotho (LS)	27%
Moldova (MD)	23%
Nepal (NP)	22%
Samoa (WS)	21%
Haiti (HT)	21%
Lebanon (LB)	18%
Kosovo (XK)	18%

(US$, Billion)

Fig. 5.1 International remittances through branchless banking (US$, billion) total remittances 2011—US$507.60. *Source* World Bank Migration and Remittances Factbook (2011)

5.3 Problematic: Climate Change, Food Security, and Disaster Relief

Forty years ago, the average growth rate of crop yields per acre was an impressive 3.5 % per year, outpacing the 2 % population growth rate. In recent years, however, the growth in crop yields per acre has dropped to about 1.5 %. Concerns over projected higher food prices and food security are well founded as growth in crop yields have fallen steadily to the point of being outstripped by population growth rates. Crop yield growth is off in part due to less arable land per capita as increasing arable land loss has been one of the effects of climate change.

Against this backdrop, it is reasonable to expect that growing climate volatility may result in increased soil erosion and associated arable land loss as extreme storms can cause several years' erosion to occur rapidly (Cox et al. 2011). Recent evidence confirms that the poor and smallholders tend to be concentrated in areas more subject to adverse climate events. Placing the problematic in perspective of the linkages between climate change and food security, from 1800 onward the commercialization of hydrocarbons allowed for an explosion in energy use and in food supply, with a concomitant population growth from 800 million to 7 billion. Climate volatility and unsustainable farming practices have contributed to soil erosion, further reducing arable land. Financial markets are sending significant price signals. The prices of all important commodities except oil declined for 100 years until 2002, by an average of 70 %. From 2002 until now, this entire decline was erased by a bigger price surge than that occurred during World War II (Grantham and Mayo van Otterloo 2011).

Linked to the problems of food production and food security is the role of smallholder production. Smallholders are the predominant source of food production, producing 80 % of the food consumed in developing countries, and one in three people work in agriculture worldwide (FAO 2013). Smallholders are subject to financial exclusion and thus dependent on informal networks to mitigate the potential risk of crop failure. Due to the inability of informal networks to mitigate the possibility of mass crop failure related to extreme weather events, the estimated 25 % underproduction due to smallholder reliance on informal networks is expected to widen further (Cole et al. 2012).

Consequently, to realize further gains in smallholder food production it is necessary to address the underlying factors that result in smallholders not planting to full sustainable capacity (e.g., financial exclusion compelling smallholder reliance on informal networks for risk mitigation). While informal networks represent an available coping mechanism for smallholders, especially those planting multiple crops, informal structures to mitigate crop failure are insufficient to address the mass failures more likely to occur with increased climate volatility (Beko and Lytle 2014). A recent study in Kenya indicates that households with access to MFS are able to manage better the effects of income shocks and that such networks expand informal risk sharing beyond one's immediate neighbors (Jack and Suri 2014). Such risk sharing is apparent in the international networks by which remittances or financial resources are mobilized after a disaster.

5.4 Modeling Financial Services and MMI

MFS pricing structures (from a private sector perspective) need to be evaluated in the context of market penetration and disaster risks. The data presented graphically can be shown as a time-series in which MFS flows intensify; data suggest that MFS adoption in developing countries follows a model in which transfers via remittances lead to the adoption of other MFS (Stuart and Cohen 2011). As discussed infra, some of this is supply-driven by MNOs, but reliability is a factor in uptake. In Kenya, Philippines, Sri Lanka, and Tanzania, money transfers between mobile users internationally have been available for the past five years; all these countries are instances in which MMI is now available (GSMA 2013).

The business model designed to address disasters is that of insurance, as distinct from the aid-based, humanitarian model. As noted, MMI is evolving rapidly. The GSMA Mobile for Development Intelligence database notes six deployments of MMI: (CGAP 2013); other examples, however, have been identified and reviewed by the Consultative Group to Aid the Poorest (CGAP) (Tellez and Zetterli 2014). In terms of the establishment of basic financial literacy, MFS has the potential to expand (both deepening and broadening) financial inclusion, by allowing individuals to establish a credit record which could then be used for loans or microinsurance.

One of the basic tenets necessary for insurance markets to exist is the ability to segment the population of potential policyholders by risk category as underwriters desire to price the cost of insurance coverage in line with an associated expected level of risk. Relative to developing countries, segmentation has been difficult as available datasets have not been as comprehensive or complete as those found in more developed economies. However, the recent rapid adoption of mobile phones in developing countries has created call detail record (CDR) datasets providing an important source of information that can be used to establish population risk profiles in that an individual's history of prepaid mobile account payment and use may serve as a proxy indicator for debt service and repayment capacity.

CDR-based credit scoring is termed airtime-based credit scoring (GSMA 2013). To date, CDR-based credit scoring models have been created by two companies, Cignifi and Experian MicroAnalytics. Both are private sector startups with an emphasis on markets where there would be development impact. Cignifi's model was an accurate predictor of default when backtested against historical lending from approximately 40,000 borrowers of the MNO's lending business, as the model's scoring correlated positively with default rates across the actual lending portfolio. Experian MicroAnalytics conducted a similar CDR-based scoring exercise with the Philippine MNO Smart and its lending partner, mBank, and is an affiliate of Experian PLC, an established credit scoring company which is publicly traded (Kumar and Mohota 2012). To the extent airtime-based credit scoring provides an effective proxy indicator, it can be incorporated in MMI deployments to provide a risk category segmentation of the potential policyholder population. The two models, although reaching similar points, originate in slightly different private sector partnerships, demonstrating the potential flexibility within such offerings.

The best practices to date on managing credit risk on airtime-based credit scoring driven loans consist of:

1. An origination credit scoring system employing variables based on airtime top-up patterns; voice and SMS usage; and other information either available directly from the borrower (e.g., income, marital status) or other sources (e.g., credit bureau);
2. A credit risk agent management system to rank agents dynamically by the credit quality of the potential borrowers introduced to a given lender to calculate and disburse risk-adjusted commissions as well as to alert agents if their clients are late on payments;
3. An automated customer management system (i.e., send borrowers payment alert notices, increase/decrease dynamic exposure to good/bad borrowers, streamline management of overdue payments);
4. An enhanced mobile interface for end clients to allow credit product management on a real-time automated basis (GSMA 2014).

The development of MMI is accelerating as MNOs are increasingly active in launching MMI product offerings (Tellez and Zetterli 2014). Competition has intensified in their traditional core voice markets, and product innovation is a response aimed at improving relative customer retention and enhancing average customer revenue realization. MMI product launch activity is most active in Sub-Saharan Africa with approximately 54 % of the product introductions surveyed. MNOs are promoting MMI products that are "free" or "freemium" (i.e., a basic "free" offer that can be upgraded to provide additional cover for a small premium) which are typically bundled with another product whether insurance, financial service, or nonfinancial product or service. From an industry perspective, MNOs' goal is to derive greater revenue from existing subscribers by requiring MMI recipients to meet minimum requirements in airtime use, mobile money transactions, or a combination of these and other activities. The business model as applied not only increases direct revenue for the MNO, but in the process bolsters return on investment from each subscriber, something certainly attractive to investors. Of the MMI products that are paid, half of these products bill via direct airtime deduction and the other half via mobile money payment (Tellez and Zetterli 2014).

Relative to insuring against the risk of agricultural loss [i.e., crop failure, loss of livestock due to extreme weather (e.g., drought, flooding)], insurance markets have been slow to develop as traditional indemnity contracts have high administrative costs to verify claims and guard against adverse selection (Cole et al. 2012). However, to achieve lower costs, insurance products have been developed where payouts are based on measurements of an easily observed index. Two index approaches of particular interest are weather insurance and area-yield insurance. Weather insurance allows coverage based on weather data (e.g., rainfall levels measured at a specific reference station) with payouts triggered when weather data meet specific threshold levels. Area-yield insurance is based on selective measurements of crop yield in a certain geographical area. A drawback of index insurance is that payouts may not exactly match customers' agricultural losses. This lack of correlation is termed basis risk (Cole et al. 2012).

Of the two approaches, weather index insurance is viewed as the less costly to provide and so has been the approach chosen to provide coverage while minimizing losses for insurers who typically operate with some form of government support (Cole et al. 2012). Rainfall index insurance was successfully piloted in 2003 in the Indian state of Andhra Pradesh with insurance underwritten by ICICI-Lombard and sold through the microfinance institution BASIX. Also, since 2007, the Indian Government's Agricultural Insurance Company of India (AICIL) has been piloting index insurance through its Weather Based Crop Insurance Scheme (WBCIS) program. In Mexico, the Ministry of Agriculture administers weather index insurance programs to provide coverage for drought-affected farmers with insured coverage of US$90 million in 2007. However, in contrast to India, the insurance contracts in Mexico are sold to state governments rather than individuals. Having state governments as the insurance policy holder adds to the range of options available to provide coverage to smallholder populations that may not otherwise be directly insurable because of failing to pass either airtime-based credit scoring screens or other analytical approaches employed to determine eligibility. Meanwhile, note most programs appear to have met with little success moving past the pilot stage when weather index insurance is sold on a stand-alone basis as opposed to being bundled with credit products (Cole et al. 2012).

Meanwhile, area-yield insurance costs may decline as airborne platform-based (i.e., satellite, unmanned aerial vehicle (UAV), drone) imagery processing is growing by orders of magnitude as it moves from manual single-machine processing to automated cloud-based analysis (Crawford 2014; Monsanto 2013). Crop yields can be monitored by refractory analysis from airborne platforms. Reduced costs for monitoring specific locations may serve partly to overcome area-yield index insurance's basis risk which may allow for expanded area-yield index insurance application. Normalized difference vegetation index (NDVI) insurance relies on indices constructed using time-series remote sensing imagery whereby moisture deficit is related to crop yield performance, an area that holds certain promise of wider application due to the technology advances discussed supra.

As to weather index insurance, Kilimo Salama (in Swahili, "safe agriculture"; henceforth "Kilimo"), is a partnership of the nonprofit Syngenta Foundation for Sustainable Agriculture, UAP Insurance, and the MNO Safaricom cofunded by the International Finance Corporation (IFC)-managed Global Index Insurance Facility (GIIF). To cut transaction costs and build trust with clients, Kilimo employs two technologies: solar-powered computerized weather stations and mobile phones. Each Kilimo client is within 20 km of a station recording data (e.g., rainfall levels, temperature, sun) every 15 min. The farm supply store owner sells UAP policies, records the purchase with a camera phone, and transmits a confirmation text message to the buyer. At growing season's end, payouts go electronically to farmer's mobile account. Kilimo is the first microinsurance product distributed and implemented via mobile phone network (Uthayakumar and Goslinga 2012).

In 2009, Kilimo ran an initial pilot to insure 200 corn farmers in the Nanyuki region of Kenya. By 2013, Kilimo insured 185,308 farmers in Kenya (65,448), Rwanda (115,550), and Tanzania (4,310) with plans to insure close to 1 million farmers in the East Africa region by 2015 (Uthayakumar and Goslinga 2012). In 2012, the development impact was material as insured farmers invested 19 % more and earned 16 % more than neighboring uninsured peers and, by 2013, 95 % of 185,308 insured farmers had loans linked to insurance coverage. In 2012, in Kenya over 30,000 farmers could access US$5.5 million in financing as they had insurance.

Further development of MFS will require greater private sector participation, and developing appropriate financial models to evaluate the specific risks in a given country, based on susceptibility to climate change and to the role of mobile industry regulatory regime overall. Following the principles set forth above in developing the specific financial models, the initial questions to be determined would be:

1. Market segmentation and product design;
2. Use of technology to reduce risk;
3. Agent network.

Recent studies have begun to link financial inclusion with social inclusion and to identify the social factors which facilitate adoption. Without a trusted agent network, mobile money service offerings cannot succeed as users would rather pay higher fees to a known agent (e.g., Western Union) than run the risk with a lower cost but lesser known agent (e.g., Xoom) that the funds transfer will fail (Smith 2013). Existence of established reciprocity and social networks drive volume and the establishment of trusted networks (including that of payout agents) are critical to MFS achieving scale. Traditional models of small-scale insurance tend to embed the product into social relationships (Dafuleya 2012). With Kilimo, a key success factor for sustainability is the degree of trust established through immediacy of policy payouts. A question of sustainability which still remains is the extent to which the development outcomes realized to date through improved production and incomes and mitigation of financial risks will persist should current climate trends worsen at an accelerating pace.

As noted, many of the principles identified for mobile money to succeed can similarly be applied to MFS (Di Castri 2013). This analysis, however, balances the private sector approach to managing possible financial risk with the regulators' focus on mitigating the risk of mobile money customers losing the money they have stored in the system (Di Castri 2013). Risk-based know-your-customer (KYC) procedures serve the dual purpose of addressing the compliance dimension with the facilitation of a forward-looking approach to risk in the context of MFS.

Technology advances in complementary services (such as geospatial) allow for enhanced monitoring and evaluation. Particularly, more frequent and higher resolution monitoring of crop cover, climatic events, and food security impact are being made possible and deployed at progressively lower costs (Moore's law). Current capability allows for monitoring smaller areas (e.g., 1 km^2 vs. 10 km^2) thus reducing index crop insurance basis risk by more closely aligning the index insurance basis location with the smallholder's actual fields.

Reviewing the various case instances, Kilimo Salama represents one material instance in which agricultural MMI has decidedly improved development outcomes and is moving into full-scale deployment (i.e., expanding base across multiple countries). The model presented here suggests that rather than approaching agricultural MMI only as a stand-alone financial product, that climate change-induced weather events could be systematically addressed through such products. Given the advent of greater weather volatility, there will be increased demand for more frequent and accurate monitoring (as discussed above with respect to NDVI). Response to climate change through private–public partnerships can be piloted, market-tested, and scaled in a relatively short time frame; the model explicated above demonstrates how various technologies developed in separate contexts can be tailored to expand financial inclusion by providing services for a historically underserved population that faces rising disaster risks posed by climate change events.

Acknowledgments The author would like to thank Paula Lytle and Tim Kelly at the World Bank for feedback on an earlier presentation which provided impetus to this paper. Additional feedback from Charles Martin-Shields and Anne Nelson is gratefully appreciated. The author would also like to thank Maj Fiil-Flynn for her perspective on mobile money and Madeline Kleiner for her research support.

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Chapter 6
Innovating for the Bottom of the Pyramid: Case Studies in Healthcare from India

Balaji Parthasarathy, Yuko Aoyama and Niveditha Menon

Abstract The much vaunted fortune at the bottom of the pyramid (BoP) has proven hard to reach. This is because realizing the opportunities provided by the BoP market faces several challenges, ranging from affordability to a lack of human and physical infrastructure. This paper argues that overcoming these challenges to achieve "frugal innovation" requires design strategies which deploy new technologies and organizational approaches. To substantiate its argument, the paper presents case studies of four firms and their innovations in the health care domain. All the cases are from India, which has emerged an ideal location for developing products and services for the BoP market. India not only has the skills to propose new technological solutions, but also a market characterized by socioeconomic diversity to demand various organizational approaches. Two cases focus on diagnostic devices and products: one is a portable ophthalmic imaging device to reduce preventable blindness, while the other is a baby warmer to lower infant mortality by preventing hypothermia. The other two cases focus on health care delivery: one relies on telemedicine while the other relies on mobile telephony to provide access for hard-to-reach populations. All four cases describe the circumstances surrounding the design, development, and deployment of the products and services. The paper will point to the challenges the firms faced, even as they successfully designed for the BoP context. For diagnostic devices, the challenge of positioning a new offering in the diagnostic devices ecosystem, especially in terms of quality and cost, figures prominently. For service delivery, the challenge is to negotiate and manage the balance between the technological and human elements in servicing those needing care. Each case provides insight into the factors responsible for the sustainable deployment of these innovations, thus enabling a degree of extrapolation of lessons.

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S. Hostettler et al. (eds.), *Technologies for Development*,
DOI 10.1007/978-3-319-16247-8_6

6.1 Introduction and Purpose

The much vaunted "fortune" at the bottom of the pyramid (BoP) (Prahalad 2004) has proven hard to reach. With markets in advanced industrial economies facing saturation, the BoP, which refers to the market opportunity offered by an estimated three to four billion customers globally earning less than US$2 a day, mostly in the developing world, has become increasingly attractive. But Aoyama and Parthasarathy (2012) point to the many reasons why tapping this opportunity is a non-trivial challenge. First, the challenge posed by affordability is a prominent reason for this segment of the population not being viewed as a viable market until recently. Second, the BoP is found in locations where infrastructure, such as power or communication networks, which are often taken for granted in industrialized contexts, is typically weak to nonexistent. Third, the BoP is not a socioculturally homogenous market, and it is characterized by relatively limited skills and low levels of literacy. With little prior exposure to technology, there are no 'lead users' who can provide the basis for the design of products and services.

To address these challenges, there has been a widespread call for "frugal innovation." Tiwari and Herstatt (2012) define frugal innovation as "new or significantly improved products (both goods and services), processes, or marketing or organizational methods that seek to minimize the use of material and financial resources in the complete value chain (development, manufacturing, distribution, consumption, and disposal) with the objective of reducing the cost of ownership while fulfilling or even exceeding certain predefined criteria of acceptable quality standards." Alas, achieving frugal innovation has proven harder than providing a comprehensive definition. It is against this backdrop that this paper argues for design strategies that deploy new technologies and organizational approaches.

The idea of relying on new technology predates the current discourse on the BoP. For instance, the ideas of people like Schumacher (1973) influenced efforts to develop "appropriate" technologies for the developing world. These technologies de-emphasized automation, scale, and capital intensity, in favor of locally controlled, decentralized, labor-intensive, and energy-efficient alternatives. But they did not gain wide acceptance for reasons ranging from limited technical transferability to weak institutional support, including insufficient funding, and a perception that they were technologically inferior (Zelenika and Pearce 2011).

What has changed since is the availability of new technologies, in particular, microelectronics based information and communication technologies (ICTs). Advances in microelectronics have physically shrunk, made affordable, and enhanced the functional potential of information processing and communication devices. It is the ability to (re)program such devices with software, for deployment in application domains as distinct as design, education, or health care, which makes ICTs versatile and gives them their revolutionary character. The application of ICTs and similar new technologies demands and expands new organizational options (Parthasarathy and Lage 2010).

In India, innovation for the BoP typically takes place in a vast informal sector in the form of *jugaad*, Hindi for local improvisation. On one hand, *jugaad* is celebrated as a reflection of Indian ingenuity in meeting needs in conditions of scarcity (Radjou et al. 2012). But grassroots innovation and its diffusion, for commercial ends or otherwise, faces challenges. The challenges include the high transactions costs for scouting and documentation, the need for value addition and finance, and ambiguous intellectual property rights (Dutz 2007).

By contrast, in recent years, the BoP has attracted the attention of the formal sector, from multinational enterprises (MNEs) with global operations, deep pockets and a reservoir of skills, to startup firms with novel ideas backed by venture capital. Such firms are also seeking partners, such as nongovernment organizations (NGOs), with a history of working with the BoP. These partnerships help firms overcome the information gaps that any effort to cater to the BoP must confront, while giving NGOs the access to new technologies to help meet the needs of their target populations.

To substantiate its argument, this paper will examine four cases from India where products and services have been successfully developed for the BoP market. These cases will show how design strategies have orchestrated the application of new technologies and the organizational changes that are required to innovate for the health care domain.

6.2 Design and Methods

India is an ideal setting to study frugal innovation as the country has emerged a prominent location for research and development (R&D) and experiments for the BoP market (Aoyama and Parthasarathy 2012). There are at least two reasons for this emergence. First, India is the world's largest exporter of ICT services, reflecting the availability of the pool of technological skills that products or services for the BoP market increasingly need. While firms traditionally turned to India for cost arbitrage, increasingly, the country is proving to be a hard-to-replicate laboratory with unique opportunities and challenges which also demand new organizational approaches. The country's population and the scale of its BoP market, absent or inadequate infrastructure, diverse sociocultural environments, the many social problems (in health, education, and other sectors), coupled with the increasing focus, acceptance, and availability of technologies (as solutions) have made India the preferred test bed for many firms. Examples of the success of India as an experimental base of global relevance are evident in such examples as General Electric's (GE) affordable electrocardiograms, Nokia's low-cost mobile phones, or Hewlett Packard's personal computer that is designed to run on car batteries.

This paper draws on case studies of four firms and their innovations in the health care domain for the BoP market in India. The first two cases will focus on diagnostic devices and products, while the other two cases will focus on health care delivery mechanisms. These segments were chosen because, despite India being a significant producer of pharmaceuticals, to the point of being considered the “pharmacy of the developing world” (Horner 2013), a large proportion of the country’s needs of diagnostic equipment and components are imported (Datta et al. 2013). India was also ranked 112 out of 191 countries for health system performance (WHO 2000).

All four cases describe the circumstances surrounding the design, development, and deployment of the products and services, and highlight the importance of balancing new technologies and organizational innovation. Even as the firms have successfully designed for the BoP context, the paper will point to the challenges they face. For diagnostic devices, the challenge of positioning a new offering in the diagnostic devices ecosystem, especially in terms of quality and cost, figures prominently. For service delivery, the challenges are to negotiate and manage the balance between the technological and the human elements in servicing those needing care. Each case provides some insight into the factors responsible for the sustainable deployment of these different technologies, thus enabling a degree of extrapolation of lessons.

The cases draw primarily on in-depth, semi-structured interviews with either the founders or heads of the firms, supplemented with secondary data from the web sites of the firms and press reports. Since the interviews were granted on the promise of confidentiality, the identity of the firms and the interviewees has been protected in the paper. The interviews focused on the processes underlying the inception of BoP initiatives, the factors responsible for decisions at crucial junctures, the specific technological and organizational initiatives within the firms, the rationale behind forming alliances to obtain domain or market knowledge, and coping strategies to meet the challenges encountered during the deployment of innovations. The interviews also provided an understanding of the visions and strategies for the replication and deployment of the innovations in other domestic and international contexts.

6.3 Results

6.3.1 Diagnostic Devices

Case A: Portable Ophthalmic Imaging Device

The first case study is a firm which introduced a portable ophthalmic imaging device that offers corneal imaging, retinal imaging, and a refractometer. It was founded in 2010 by three employees of a MNE who wanted to concentrate on preventive healthcare. The device, among the first of its kind, was developed to address the common diseases (diabetic retinopathy, glaucoma, cataract, and cornea problems among others) which are responsible for the high percentage of preventable blindness (about 80 %) in India amidst a low doctor to patient ratio (about 1:60,000).

The inspiration for the diagnostic device came primarily from a talk attended by two of the founders. The talk was delivered by Dr. Govindappa Venkataswamy, an ophthalmologist and the founder of the Aravind Eye Care System, whose efficiency in providing affordable, large scale, quality health care has led to it being described as "the McDonalds of health organizations" (Pahls et al. 2010). The talk emphasized the importance of early diagnosis to reduce preventable blindness in the country. The central problem identified by the doctor was the lack of reliable, portable equipment that would help untrained personnel diagnose diseases in rural areas. Subsequent conversations with the doctor, extensive research, and collaborations with hospitals, reiterated two factors hindering diagnosis and treatment: insufficient doctors to cover the rural population, and the difficulty in diagnosing non-cataract diseases in the field.

Typically, hospitals reach wide swathes of the rural population by hosting periodic eye testing camps. While these camps help cataract patients, for whom the treatment is fairly simple and quick, more complicated diseases require trained ophthalmologists and nurses. They also demand extensive follow-up, currently missing from the way eye camps are conducted. As a result, the conversion rates from diagnosis to treatment in rural areas are low. In essence, a high proportion of rural patients do not seek treatment despite being diagnosed with eye disease.

There are many reasons for this. The first is affordability. Second, diagnosing the more severe diseases can take hours. The time that it takes to dilate the pupil, to be examined by a doctor, to test for intraocular pressure, and then to wait for results, is often too long for patients who face opportunity costs in terms of lost income. Third, social reluctance to address one's health problems has led to a persistent culture of denial even before coming to a diagnostic center. A vast segment of the rural population believes that seeking diagnosis can only invite problems. As a result, patients either do not take the diagnosis seriously or they delay treatment until it is impossible to negotiate daily work. Usually, by this time, the treatment is unlikely to succeed.

Consequently, it became evident to the founders that it is important to get more personnel with minimal ophthalmological training on the ground to quickly identify the more serious patients and send them to hospitals, rather than trying to provide extensive diagnosis in the camps. This would improve efficiency and ensure that more resources are spent (by the patient and supporting organizations) in treatment rather than in diagnosis. Similarly, it is important to provide information to patients about the severity of their condition, and give them tangible proof, say, in the form of printed images of their eyes to showcase their problem, to convince them to pursue treatment. More efficiency in diagnosis also makes it possible to screen a larger proportion of the population within the same time period, thereby improving the chances of treating those ailing with eye disease.

Besides the background work, the personal histories of the founders also helped with understanding the needs of their potential patients in a more intimate fashion. Since two of the three founders originally hail from rural areas, they were able to draw on their own experiences in accessing health care, and understand the economic and social constraints that rural populations typically face. The ability to "relate first hand to the rural needs," also influenced their decisions.

It was thus that the cofounders decided to establish a firm to develop a device to address this gap in the market. In addition to meeting the above criteria, the emphasis was on creating a low-cost and rugged device as the primary markets are rural hospitals and health care centers that service poorly connected and economically disadvantaged communities. The ophthalmological device that has been designed from scratch can detect five major ailments including cataract, diabetic retina, and glaucoma. It also permits accurate refractive index measurements and can provide a prescreening report. To minimize loss of accuracy that can come with movement of parts as the device traverses uneven rural roads, unwanted optics has been eliminated in favor of solid-state electronics.

Within two years of introducing this device into the market, the firm has over 30 installations across the country. The device has proven highly reliable on the field and consumes much less power when compared to similar devices. The diagnosis of various diseases which required up to 45 min with other procedures and machines has been cut to 5 min because the device is noninvasive and no dilation is involved. The cost of screening has fallen from Rupees 350 ($\sim$US$6) to less than Rupees 50. There are also improvements in conversion rates because of the added feature of printing out the results of the eye exam. With these printouts, the assistants are better able to explain the problems and advocate immediate treatment.

Conceptualizing the device was not a challenge for the founders. In their statements, they expressed confidence about the knowledge base from which the device is derived. They argued that there are many researchers in this field and the relevant information that they needed was easily accessible through the doctors who shared their desire to make a difference. They also established a research center, from which four patents have been filed during the development of the device. While the founders are confident of meeting any technological need, it is questions pertaining to scalability, financing, and sustainability, which have been their primary concerns from the beginning.

One aspect of scalability was the founders' limited understanding of optical device manufacture. To overcome this, they were able to use their networks and knowledge from working in MNEs to identify a partner who could make the device to specification. But there were challenges when it came to financing and market acceptance. As mentioned earlier, the diagnostic equipment used in India is largely foreign made and expensive. The firms faced resistance from hospitals who were hesitant and skeptical about the quality of a product that was on offer for a fraction of the price of other similar products. The founders had to combat the widely held belief and perception among hospitals, doctors, and patients that inexpensive equipment is likely to be faulty. Given the option between cheaper Indian brands and more expensive foreign brands, customers are likely to pick the latter as a proxy for better quality. To fight this problem, the firm went about gaining acceptance with the key stakeholders, so that their opinion and feedback on the equipment could be used to enter unchartered territory. Eventually, the positive reception by their early clients provided word-of-mouth advertising for the product.

Currently, the firm is in the process of building a platform to expand the range of the device to detect early signs of diabetes, problems related to nephrology, and other neurological problems. It is also planning to venture into telemedicine by building cloud-based data centers that can connect doctors with patients in remote locations. As testimony to the early success, the firm obtained US$5 million from two venture capitalists (IDG Ventures India and Accel Partners) in the early stages of formation.

Additionally, they are examining the possibility of expanding to similar environments in South East Asia, Africa, and South America by working with NGOs, such as the Bill and Melinda Gates Foundation, and the World Health Organization (WHO). For example, they would like to be associated with the WHO initiative to eradicate blindness which, they argue, aligns well with the capabilities of their device and their personal passion. They have already started the expansion into Mauritius. The firm is also starting to collaborate with universities in North America and Europe to expand the research and the range of applications of the device to more affluent markets.

Case B: Portable Baby Warmers

One in three babies born in India is likely to develop hypothermia because of complications related to premature birth or low birth weight. Incubators, or radiant warmers, typically expensive, and dependent on electricity, have been the only options for hospitals and parents so far. The second case study is a firm that introduced a portable baby warmer which does not rely on the continuous availability of electricity to warm premature and underweight babies. The alternative resembles a sleeping bag, and is so simple to assemble and use that, after it was introduced primarily for hospitals, it was quickly modified for use by parents themselves.

The idea for the baby warmer came out of a 2007 design course that the co-founders were enrolled in while pursuing their graduate degrees in a university in the United States (US). The students in the course were asked to design an incubator in collaboration with an NGO in Nepal. When traveling through Nepal to understand the context, they found that babies were dying in rural and semi-urban areas despite the availability of incubators provided by international donors. This was because the incubators had ceased to work and were being used primarily as file cabinets. The incubators could not be used as intended due to problems such as the lack of spare parts, unreliable power, or the lack of local skills to mend the devices.

What they saw in Nepal convinced the founders that making something cheap cannot be the focus of any BoP initiative. What can be cheaper than equipment donated for free? To avoid confusing needs and solutions, they identified the underlying problem—in this case, keeping babies warm—and reframed it within the constraints of the local population so that the ensuing product could fill the need effectively. Unfortunately, the prototype they developed was not well received by the NGO. Reluctant to let go of what they considered a great idea, the cofounders decided to form their own NGO in 2008 to take their idea to a larger audience. Clinical trials began in early 2010 and, since the introduction of the device, about 20,000 babies in Africa and India have been serviced by these infant warmers. The device and the firm have also won many awards.

The device has many selling points. First, it costs Rupees 15,000 ($\sim$US$250) compared to imported incubators which cost at least Rupees 100,000. Second, in a target market with limited access to electricity, doctors or technical expertise, the device is robust and is easy to use. Once the pack, made of phase change material, is preheated and inserted into the warmer, it releases heat uniformly to keep the baby at a constant temperature for six hours. There is neither a danger of babies coming into direct contact with live electricity, nor do nurses and support personnel have to constantly check and measure the baby's temperature. The effort to teach primary care providers, whether they are parents or nurses, to use the product correctly has also been reduced since wrapping the product around the baby resembles a traditional swaddling technique. Thus, by using the context of resource-poor environments as strengths, rather than viewing them as limitations, the firm has been able to highlight portability and independence from grid power as unique selling points to the widely prevalent problem of high infant mortality rates caused by low birth weight and premature births.

Reflecting on their motivations behind the venture, one of the founders asserted that they have always been fueled by both the social cause of lowering infant mortality rates, and ensuring the profitability of the device. To keep this focus, they research the market carefully and pay attention to the design of the product and the entire supply chain. Since their primary motivation is social, they target under-served communities. However, they choose not to deal with the absolute BoP, as it is usually not financially viable, and these populations are particularly hard to reach both spatially and socially. So they typically settle on a "sweet spot" between the financial sustainability of the venture and their social goals. One of the ways in which they identified the "sweet spot" for the baby warmer was to focus exclusively on those small towns and large villages in India with a significant percentage of their target population, and with enough physical infrastructure and human resources to ensure sustainability.

The dual goals of the founders led to the adoption of a hybrid organizational structure in 2012. The NGO was complemented by a newly created for-profit firm, with responsibility for manufacturing, distribution and sales of devices. This entity also conducts R&D to create new low-cost maternal and child health innovations for BoP markets. The NGO is primarily responsible for advancing maternal and child health by delivering and advocating for innovative health solutions to the world's most vulnerable populations.

The firm is currently focused on establishing relationships within the Indian government. Since the government has a larger health infrastructure than any other stakeholder or actor in India, the firm wants to ride on the government networks to scale their device across the country. Given that half of all premature babies born in the world are born in India, focusing on the Indian market is prudent in their opinion.

The firm wants to enter other markets in the world only after understanding the Indian market, because it believes that most African countries, or countries such as Afghanistan, Haiti, and Somalia, lack the health infrastructure that India has, although their needs may be as acute. To work in countries where sales and market operations is not as well developed as India's is not currently feasible. However, the NGO arm of the organization collaborates with partner organizations in these countries to build relationships that may allow for expansion in the future. Additionally, the for-profit arm relies on an American MNE, with extensive resources and a global consumer base, to serve as a distribution partner in South East Asia.

6.3.2 Service Delivery Systems

Case C: Telemedicine

The third case study is a firm that delivers radiology services remotely. The two cofounders are physicians who obtained medical degrees in the US, and also worked in various US hospitals, before moving to India in 1999. Initially, the cofounders were restricted to analyzing images sent to them over the internet by their previous employer. When they established the firm in 2002, other US hospitals who were unable to get enough personnel to fulfill their radiology needs during night shifts began to contact them over their web site. The firm was able to use the time difference between the two countries to service these American hospitals. The service was subsequently accredited by the US Joint Commission on Accreditation of Healthcare Organizations and by Singapore's Ministry of Health.

In 2010, the firm established a technology division to develop software solutions for teleradiology and telemedicine. The flagship product, which was developed with input from the firm's radiologists, is a cloud-based system that integrates a radiology information system (RIS) and a picture archiving and communication system (PACS). The integration makes it possible to retrieve patient data along with images, unlike traditional radiology systems that use disparate RIS and PACS. The software is optimized for multisite, multi-radiologist establishments and can be integrated with any existing system. It enables fast downloads even at peak loads and with limited bandwidth. Recently, the firm started collaborating with a major networking MNE to develop a new telemedicine platform that will allow a transition from using only video or images to using instrumentation (like a heart and blood pressure monitor) for remote diagnosis.

As the firm established its credentials in the US, it began to turn its attention to the gap in radiology services in India. Living in India, the founders soon realized that doctors, especially radiologists, are rare in remote parts of the country, and that telemedicine could help in diagnosing and treating underserved populations. Moreover, they realized that since medical training is uneven across the country, the quality of the doctors is also an issue. Additionally, given the vast population, and the limited number of good doctors, the time that can be devoted to providing quality care, even to the patients who are able to access hospitals and doctors, is also limited.

Using the same service delivery platform that they use for their US clients, the firm started establishing relationships with hospitals in remote parts of the country to provide radiology and other services. They found that although the availability of bandwidth and other infrastructure can constrain the application of telemedicine in these new contexts, the ability to manage workflows is a more significant challenge. It is here that the background of the founders proved valuable. As physicians, they have always been particular about generating reports that help the user (also a physician), and conscientious about testing their service within the medical community. Being part of the medical ecosystem, they are also in the position of being able to constantly modify the platform to suit the needs of doctors in various contexts, facing different local constraints. Thus, to overcome the reluctance of doctors and hospitals to move away from familiar software systems to new systems, the firm ensures that the platform that is developed can integrate with a variety of commonly used software to minimize the disruption for doctors unused to newer systems.

Another benefit of paying close attention to workflow is that the platform permits even low-skilled persons, such as doctor's assistants, to scan and send images across to the firm. Since the firm also established a hospital in 2007 in Bangalore, the doctors available on premises are able to remotely diagnose the patients, and the assistants are able to locally administer the required treatment. In this manner, they address the lack of doctors in many areas. But this approach has not been without challenges. For instance, in India, and in many African countries, where there is an abundance of low cost but inadequately trained labor, redundancies are built into the system of diagnosing patients. Since training and maintenance are an integral part of the service package, how best to change the labor intensity of older systems has proven to be a tricky question.

In 2007, the firm also established a not-for-profit entity to provide teleradiology support to hospitals in rural/semirural and underserved areas in Asia that could not obtain on-site radiology coverage. The goal was to provide a higher standard of diagnosis and care to such communities. Financial sustainability of this new entity relies on a Robin Hood model where affluent clients, such as US hospitals, subsidize the services provided to rural and poor customers. Recently, the firm has established rural telemedicine and training centers in collaboration with local health care providers in the Indian states of Karnataka and Madhya Pradesh as a first step towards building a national network. The technology division of the firm is also expanding the platform functions to include education and online teaching services so that qualified doctors can train and mentor medical students. The firm has also developed an e-teaching module for medical students in Africa and elsewhere, where access to good teachers or training materials is limited.

Case D: mHealth

The fourth case study is a firm that was founded in 2001 by two doctors and two computer scientists in the US to use mobile technologies to address the needs of the BoP market. Initially, since the firm addressed specific problems and projects, mostly in Africa, its technologies were customized to the individual user. A new phase of the firm began when it started to piece together the work it had done to create a mobile platform whose five primary functions are collecting data, managing clients, engaging with multimedia, managing applications and workers, and active data management. The firm identifies itself as a technological provider of a platform whose strength is its flexibility to deal with various contexts, making it possible for any customer, in any part of the world, to use its services. Despite the professed agnosticism of the platform to application domains, it has been used primarily in healthcare. The platform allows frontline workers, such as community health workers, to track cases and support their interactions with clients over time.

Currently, the platform is used by various actors, such as NGOs, families, communities, and individuals, for a range of healthcare needs and services including personal medical histories, reminders for intake of medicines (in the case of AIDS), health information and education, logistics management, financial services, data imaging, and data modeling. Recently, the platform has started to provide healthcare informatics that enables other stakeholders to usefully engage with commercial, academic, and government organizations.

The firm provides continuous and prompt support to all user organizations. Providing support serves two roles. First, since the firm undertakes full application development for its customers, in addition to the broad services it provides, customers can use the platform in various domains for any function. Second, since the platform is open source, any customization for clients feeds into expanding the platform. This expansion allows for greater diversity of service to future customers who can then modify and use the platform in similar ways. Indeed, as a consequence of this characteristic, the firm has started working on mobile phone diagnostics, by relying on images sent to doctors.

The platform is especially designed for a resource-poor environment. It does not assume mobile connectivity at all times and allows customers to operate offline and transfer data into a data center only when connectivity is restored. While this makes the platform eminently useable in any BoP market, the primary attraction of India for the firm is social diversity, the scale of operations, and the acceptability, familiarity, and availability of mobile technologies in the country. As a result, the strategies that the firm adopts in India are different from those in the other resource-poor environments that it works in, such as Mozambique and Senegal. Unlike in Africa, the firm spends little time in training, outreach, or 'educating' organizations in India on the possibilities and potential of mobile technologies. The Indian office finds that they have customers who walk in, based on word-of-mouth, and other means of advertising.

6.4 Conclusions

What does it take to develop products and services for the BoP market? The cases provide insights into the design strategies used by the four firms to overcome the challenges posed by the BoP market and how they orchestrated the deployment of new technologies and organizational approaches to that end. The paper will close with a discussion of the larger implications of these lessons for innovation.

In addressing the challenge of affordability, the firm selling baby warmers (Case B) makes clear that not all segments the BoP are viable markets. As a founder of that firm put it, one must find a "sweet spot" where meeting the dual goals of catering to the underserved, and ensuring the financially sustainable provision of a product or service, is possible. The precise location of that "sweet spot" may well depend on the nature of the product or service. To cross-subsidize operations until there emerges some degree of affordability (as is the case with the baby warmer (Case B) in Africa) is an option. This is also evident in the Robin Hood model adopted by the telemedicine model (Case C) to provide healthcare for poorer populations in Asia by relying on earnings in more affluent markets.

Faced with weak to nonexistent infrastructure, typically supplied by public utilities, firms make efforts to minimize the use of the infrastructure in short supply. The ophthalmic imaging equipment firm in Case A minimized the use of optics in favor of solid-state electronics due to poor quality roads. With the baby warmer (Case B), the lack of reliable and continuous electricity supply forced the firm to turn to new materials as an alternative to keeping babies warm. Similarly, in the case of the mHealth platform (Case D), due to problems of mobile connectivity in remote areas, offline operation is an integral feature and no assumptions of continuous connectivity are made in the design of services.

The different experiences of the mHealth platform (Case D) in Africa and India also emphasize the heterogeneity of the BoP market, especially with respect to the acceptability, familiarity, and availability of mobile technologies. Firms deal with such heterogeneity in many ways. The firm with the mHealth platform (Case D) expends much less effort on training, outreach, or 'educating' organizations on the possibilities and potential of mobile technologies in India compared to Africa. The firm with the baby warmer (Case B) also deals with the variations experienced within and across countries very strategically. The firm, on one hand, relies on its NGO arm to supply baby warmers in Africa, whereas in India it has attempted to find a sweet spot within the BOP market largely through its for-profit division.

Acknowledging that the market is characterized by limited skills and low levels of literacy also forces firms to design with the available human infrastructure. This is what led to the design of the ophthalmic imaging device (Case A) primarily for use by relatively untrained technicians. Lowering the demands on highly trained people for routine diagnosis frees the firm to attend to the more medically demanding cases. Likewise, the device offers printouts of the results of eye examinations to enable the technicians to explain the implications of a disease to skeptical patients. In the case of the telemedicine (Case C) as well, the firm's platform paid close attention to the radiology workflow to permit even low-skilled persons in remote locations to scan and send images across.

Evidence of seeking new technologies to overcome the challenges of the BoP is found in all cases. In the case of the ophthalmic imaging device (Case A), there were two aspects to designing a product that could respond to the conditions of rural India. The first was the use of ICTs in the form of solid-state electronics, instead of relying on optics to diagnose eye diseases. The second was the ability to investigate five major diseases in a noninvasive manner so that dilation of the eye and the subsequent inconvenience was eliminated. For the firm selling baby warmers (Case B), it would not have been possible to make inroads into the market, but for conceptualizing the baby warmer around phase change materials which can absorb heat and then release it uniformly. In the case of telemedicine (Case C) and the mobile health platform (Case D), the technology provided an unconventional means (at least for the BoP market) to deliver services to remote locations with little human or physical infrastructure. In the first instance, it is the internet whereas, in the latter, it is the ubiquitous mobile phone. A common feature across all cases is that the development and deployment of globally validated technologies is by skilled and formally trained professionals, even if the inspiration is drawn from the informality of their surroundings.

While there is little doubt that new technologies, especially ICTs, have been critical to addressing the BoP market, even more critical has been the need to address the demands for new organizational forms. As the founders of the ophthalmic imaging device firm (Case A) explained, they learned all that they needed to know about ophthalmology quickly and then set about building the device by drawing on their years of experience as employees of MNEs. But, despite their training and experience, gaining acceptance for their innovation was a challenge.

Finding a place in the device ecosystem not only required demonstrating superior performance but also overcoming the prejudice that imported and pricier devices were necessarily superior in terms of quality and fit. Acceptance had to wait until positive testimonials from early clients provided word-of-mouth advertising. The firm selling baby warmers (Case B) is an example of the same challenge manifesting itself differently with a different solution. Introducing a new device, without sacrificing on either the social desire for its widespread acceptance, or the business desire for financial sustainability of the venture, demanded a hybrid organization that combined a commercial entity and a not-for-profit entity. This allowed the venture to pursue goals that are seemingly at cross-purposes.

With healthcare delivery, the organizational challenge is about maintaining a balance between the technological and human elements when servicing those needing care. In the case of telemedicine (Case C), a key aspect of the delivery of teleradiology services is to reorganize the workflow and to make the platform easier to use by less skilled professionals. While this meets the goal of remote diagnosis and eases the local delivery of treatment, it raises questions about how best to modify existing workflow of patient diagnosis which, in many parts of the developing world, has redundancies built into it as a means of coping with skill shortages.

For the mHealth platform (Case D), the problem is overcome by merely providing a technological platform that users are free to deploy as they see fit. In one respect, the firm is not delivering any tangible medical care. But from a different perspective, it is an elegant solution. Since the platform is open source [in contrast to the proprietary platform in the case of the telemedicine (Case C), every new or innovative use by a customer allows the firm to incorporate the features of the innovation into the platform. In other words, by not dictating the provision of services, the firm caters to a broader audience and is able to expand the utility of its platform.

If new technologies and organizational structures are in evidence, and each of these cases shows the different opportunities and challenges in catering to the BoP market, what are the implications for frugal innovation? Perhaps the best answer comes from the cofounders who built the baby warmers (Case B) who argue that an exclusive emphasis on costs can, ironically, prove costly. As their experience in Nepal showed, while donated devices were notionally free, the costs add up as one takes into account the physical and human infrastructure in the environment. Instead, the essential design strategy for the BoP market is to shed all preconceptions to identify the critical health needs of the population and then reframing those needs in terms of the surrounding social and environmental constraints. Once the needs are understood, new technologies or organizations can help achieve innovation that is effective and minimizes long run costs.

Even in the case of ophthalmic imaging device (Case A), instead of dismissing the reluctance of rural patients to seek follow-up treatment, a sensitive understanding of the price they pay for long waits was critical to designing a device that generated images to convince them of the long-term benefits of seeking treatment. These ideas resonate with what Polak and Warwick (2013) call zero-based design: starting from scratch to create innovative products and services tailored for the very poor, armed with a thorough understanding of what they really want and need, and driven by "the ruthless pursuit of affordability."

Acknowledgments The case studies described here are drawn from a larger study "The Global Shift in R&D Alliances: Multinational Enterprises (MNEs) and the Quest for the BOP markets." The study is supported by a US National Science Foundation Grant (BCS-1127329) and has the first two authors as Principal Investigators. Interviews for the four cases were conducted on 16 July 2012, 25 June 2013, 10 July 2012, and 18 June 2013, respectively.

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Part III
Open Source-Open Access-Open Innovation

Chapter 7
Promises and Perils of Open Source Technologies for Development: Can the "Subaltern" Research and Innovate?

Sachiko Hirosue, Denisa Kera and Hermes Huang

Abstract The paper summarizes the current state of the "Openness Paradigm" for development, with a focus on open source hardware and the related issues of open science, open data, and open access. It focuses on how such efforts support more equal collaborations between North and South on open science and citizen projects. It also discusses these efforts as an example of an inclusive Research and Development (R&D) agenda different from the traditional practice of technology transfer, which enforces the hierarchical notion of "development." We apply the present postcolonial studies discourse along with contemporary discussions in the west on public participation in science, as a framework to discuss Technology for Development (Tech4Dev). Thus, bringing attention to nontraditional formats and institutions, and new institution–community relations, as examples of a more democratic and inclusive Tech4Dev agenda.

7.1 Introduction

The attempts to discuss science and technology in the Global South must address the "subaltern" issue before discussing the promises and perils of the Open Source Technologies. The "subaltern" issue refers to the famous essay by Spivak (1988), which posed the difficult question of how to resist epistemic violence behind

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S. Hostettler et al. (eds.), *Technologies for Development*,
DOI 10.1007/978-3-319-16247-8_7

various attempts to give voice and agency to the “Other” (developing, Third World countries). The “Other” is not simply a fellow human or a group with whom we happen to live on the same planet waiting for an opportunity for mutual recognition and appreciation. To question this contemporary fantasy of the “generous” acts of recognizing and admiring the “Other” in the unproblematic plurality of the worlds, Spivak uses the Gramscian term of the “subaltern” (Gramsci 1971). The “subaltern” as a group bears witness that there are no neutral “Others,” but a shared history of various social, political, economic, cultural, and other forms of exclusions and oppressions, which need to be addressed before we engage in any emancipation campaign.

The epistemic violence behind the concepts of knowledge, reason, and we shall add development, lies in the fact that these categories are imposed as universal and somehow neutral, with good intentions, while forgetting their geographical, cultural, but also historical and economic contexts and agendas. How to control and even resist the Universalist aspirations behind the attempts to enable science and technology as tools and even goals of development in the Global South? How to resist the reverse (we could even call it “orientalist” (Said 1978; Adas 1989) fantasy of some indigenous knowledge and grassroots innovation (Rata 2011; Singh et al. 2012) as something, which needs recognition and care for its exoticism? Just as there are no neutral “Others” outside of common history, there are also no human activities, practices, or forms of knowledge, which are unproblematic in its past and future agendas and aspirations. In this sense, the challenge is whether the “subaltern” can research and innovate without adopting these agendas of the current power structures with their uncanny colonial roots.[1]

The discussions about the possibilities of research and technology innovation in the Global South often reproduce various forms of epistemic violence (Forero-Pineda 2006; Guédon 2008; Holmgren and Schnitzer 2004). We often summarize them as variants of the discussions on the deficit model (Freeman and Perez 1988; Byerlee and Fischer 2002; Forero-Pineda 2006). The current forms of epistemic violence in the discourses upon technologies for development all start with the following juxtaposition. Research and Development (R&D) and innovation are buzzwords, which frame the discourses of development in the west, while the Global South is often perceived as place of deficit, lack and digital amongst other divides (Warschauer 2003; Strover 2003; Young 2001), which simply await to be bridged. The epistemic violence behind this framework derives from defining technologies and science as something that is always transferred and applied in the South by the help of various donors, corporate responsibility programs or other innovators from the west.[2] In the best-case

[1]This pattern unfortunately is hard to expel, and can be seen reproduced across class, race, within a country.

[2]This transfer takes the form of collaborations, educational and empowerment programs, and material donations, but also conveniently as a new market for the technological innovations and solutions made by the Global North for the South.

scenario, the originators of R&D collaborate and work with the local communities to interpret their "local needs."[3]

It was exactly these forms of epistemic violence and vicious circles, which we decided to question in our panel "*The Openness Paradigm: How Synergies Between Open Access, Open Data, Open Science, Open Source Hardware, Open Drug Discovery Approaches Support Development*?" for the 2014 EPFL-UNESCO Conference on Technologies for Development (2014 Tech4Dev). We connected the discussions about the science in the Global South with the "Openness Paradigm," which allowed us to ask how science should be practiced in any community in a more critical and inclusive way. We looked into the synergies between various movements supporting open access, open data, open science, and open source hardware, to show how these emergent practices driven by the "Openness Paradigm" can reframe our ideas of development and science. We were interested in a type of agency, which can question the hegemonic views of science and technology development, and instead of lack, show examples of success and alternatives to how science is practiced in the west.

7.2 Subaltern Research and Development and Alternative Models

The speakers of the panel brought together material for a genuine reflection on what it means to know and innovate in a different context. The presentations by Gabriella Levine (United States) on water monitoring (Levine 2014) and Nur Akbar Arofatullah (Indonesia) on open hardware laboratory equipment (Arofatullah et al. 2014a) showed the promissory aspects of open source hardware for open science efforts. Open source hardware is defined as "hardware whose design is made publicly available so that anyone can study, modify, distribute, make, and sell the design or hardware based on that design" (OSHW_a, n.d.) and it offers an ideal tool for designing cheaper and customizable scientific equipment. In discussing her open hardware project, a biomimetic swimming robotic snake for education, research and environmental interventions, Levine pushed the issue of collaborative design iteration and community engagement. Her water robots, which can host sensors for monitoring water quality and other research, are all available through the sneel instructables site, which also shows the dissemination and impact of these tools with examples of replicated designs by people interested in citizen science. Levine discussed the hands-on workshops and hackathons related to Open Source Hardware Association (OSHW) projects as more decentralized and horizontal models of

[3]We do not intend to claim that Spivak's issue with the impossibility of the subaltern speech (and research) can be resolved. Despite this framework, we do believe there is value in the attempts to try and often fail in such efforts, for the sake of experiencing the paradoxes and opening the debate of what can be done further.

sharing knowledge and know-how and emphasized the empowering aspects of hands-on learning and technological innovations for people to "do their own science" (SciDev.Net 2014a). These concepts manifest in living practice was Arofatullah's presentation on open source laboratory equipment in Yogyakarta. Echoed in his statement, "*If you cannot buy one, let us try to build one, and learn valuable new skills in the process*." (SciDev.Net 2014b), the locally developed Do-It-Yourself (DIY) and Do-It-With-Others (DIWO) open source lab equipment fills the lack of resources in the university laboratories in Yogyakarta pointed out by Irfan Dwidya Prijambada's (Indonesia) presentation (Arofatullah et al. 2014b). With these self-made equipment, one can set up a full microbiology laboratory, with sterile hoods, shakers, PCR[4] and electrophoresis setups for molecular biology, to digital microscopes. Arofatullah is also active as one of the transdisicplinary practitioners in Lifepatch, citizen initiative in art, science and technology, where face-to-face hands-on workshops, both a learning and a teaching opportunity beyond the university, play an important role in building on the knowledge documented online. The alternative formats of learning and sharing (hackathons, barcamps, workshops, dissemination portals) feed knowledge and know-how, which have spread beyond the directional North–South axis, across cities and countries in the Global South, where the discussion of North–South becomes irrelevant.

The presentations by Nanjira Sambuli (Kenya), and Scott Edmunds (United Kingdom, China) explained the role of open data with special focus on better governance and genomics research. While the presentations on Indonesia and OSHW showed the value of community in open science projects, the example of open data in Kenya showed how scientific and technological progress are often part of democratization process. Kenya in this sense is a pioneer in supporting political transformation and personal empowerment through democratic and transparent forms of crowdsourcing data. The case study of the 2013 elections in Kenya presented by Sambuli compared active versus passive crowdsourcing suggesting a viable role for each type of participation (Sambuli et al. 2014). By actively recruiting participants through an open call, one gained less noisy actionable data, while passively "listening" to social media feeds gave the pulse of local events. This has also very important implications on engagement of citizens, the design of Open Science projects, and any project using the open data approach. Edmunds presented several examples (BBSRC media, n.d.; O'Brien 2012; MacLean et al. 2013; Li et al. 2014), in which China had a major impact as a pioneer in genomic research with their open data publishing efforts (Beijing Genomic Institute and Gigascience, respectively). The unprecedented efforts around the 2011 *Escherichia coli* 0104:H4 outbreak in Germany starkly highlights what timely outcomes can be achieved with Open Data and crowdsourcing genomic research supported by such an unlikely leader for massive scientific efforts from Shenzhen, China. Edmunds discussed the importance of the release of the initial sequence to the public domain, which

[4]Polymerase chain reaction (PCR), especially the quantitative PCR, now on kick-starter, is useful for genetic engineering, diagnostics, DNA fingerprinting, etc.

mobilized professional and citizen scientists to collaborate successfully to identify the strain, develop diagnostics and treatment (Edmunds et al. 2014). The standard politics and economic pressures of journals and patents would have altered the timeline and outcome. Here we see again, the Global South as a pioneer and model for scientific research efforts.

In this respect, the most striking was the presentation by Prijambada on the model of financing research and impact assessment implemented by the University of Gadjah Mada (UGM, Yogyakarta, Indonesia). UGM and other universities in Indonesia have an "Office of Research and Community Development" whose role is to organize groups of students and researchers across various often isolated communities on the islands in Indonesia and to help with various development tasks related to science and technology. The impact of university research is assessed by the impact on the communities. This is in sharp contrast to the prevalent models, which assess the university's impact by the research published in high impact journals with little if any concrete beneficial effects on communities given the resources expended (Alberts et al. 2014). The emphasis on applied research and spin-offs (McDevitt 2014), which binds research to deliver commercial success measured by short-term monetary returns on investment present a complete failure when facing immediate challenges of the communities shown in Prijambada's presentation. The presentation also showed the unlikely merging of the contemporary DIY and DIWO approaches to science through these established student community services in Indonesia. In the educational curriculum at UGM, required community service plays an important part in the social awareness of their graduates. As a highly regarded public university, they take the stewardship in weaving the complex networks of university, rural communities, and the nonprofit sector, without excluding new entrepreneurship opportunities (OSHW_a&b, n.d.).[5] This model of university–community relationships allows university research to respond to community needs.

7.3 Summary

The whole panel provocatively showed that the Global South is not only an alternative model for research and innovation efforts, but can actually inspire and lead the efforts in science and technology, especially in terms of its impact on communities. The Global South impress upon us as being a progressive site, where the future of science and community is reflected and questioned in a radical manner, which partially echo the postcolonial concepts of the "subaltern." The R&D in the Global South is bringing a form of subversive, almost subterranean concepts of science (and community) often outside the enlightenment and "modernization"

[5]OSHW states "Open source hardware gives people the freedom to control their technology while sharing knowledge and encouraging commerce through the open exchange of designs."

project (Banuri 1990), which share some of the values of DIY science as it is practiced in maker and hacker communities (Kera 2012, 2014). We are witnessing living, experimenting communities, which support the progressive and radical ideals of open science, open data, open technologies, and citizen science engagements with the enterprise of "Science." These approaches, upholding the "Openness Paradigm," are social as much as technical, which are objects and machines, as much as rules and licenses, hold the key to true development both in the South and North.

Still, more work needs to be done in terms of governance of these tools and emerging institutions. The direct connection of community building and prototype testing, the new global research networks around emergent and low-tech equipment, new practices of data publishing and sharing, all support the R&D innovation in developing countries. However, without testing, calibrating and making assessment, these tools will never resolve the actual problems or become scalable. All papers made calls for alternative, more holistic metrics for assessing research in the Global South and more South to South cooperation. An example of such an assessment was proposed by Sambuli et al. (2013) for crowdsourcing. The last paper presented, discusses the limits and problems related to these more democratized and publicly engaged forms of science and innovation. Kate Ettingers' presentation on "Open Issues and a Proposal for Open-source Data Monitoring to Assure Quality, Reliability, and Safety in Health Care Devices Targeting Low- and Middle-income Countries" (Ettinger 2015, Chap. 8) was a call for action for testing and calibrating open source tools to create some form of regulation, which will not betray the communities with a new hegemony. The paper made very clear that we need to collaborate and define new metrics for quality, reliability, and safety in Open Hardware equipment, especially for health care devices.

We concluded with our hope that future collaborations and funding schemes will address the need for a middle ground between science oligarchy, versus complete anarchy in open data and hardware. Our panel with the grouping of papers by scholars from various regions and disciplines demonstrates that the Global South can not only research and innovate, but also actually challenge the status quo of how science is done in the Global North. By carefully rephrasing Spivak's question, we posit that the "subaltern" can not only research and innovate, but they can dare to question what research and innovation means in the present economic and political climate (Brossard et al. 2005; Byerlee and Fischer 2002; Cohn 2008; Conrad and Hilchey 2011; Cooper 2012; Cooper et al. 2007; Dickinson et al. 2010). Rather than to navigate and negotiate current patent and publishing landscapes, which preserve the dominance of a few in scientific research and innovation, embracing the open source and open data technologies gives the opportunity to critically examine and reimagine the models of scientific research, economics and development. The science of tomorrow is science where precedents and transformations will come from unexpected places.

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Chapter 8
Open Issues and a Proposal for Open-source Data Monitoring to Assure Quality, Reliability, and Safety in Health Care Devices Targeting Low- and Middle-income Countries

Kate Michi Ettinger

Abstract Health care entrepreneurs who design medical devices and mobile health applications for emerging markets face difficulty when deciding how to demonstrate the safety of their products. Many middle and low-income countries have no uniform system to address safety. This paper presents findings from 40 interviews with stakeholders involved in device development. It illustrates multi-stakeholder perspectives on quality, reliability, and safety (QRS) issues for health care devices designed for low- and middle-income markets. The paper identifies key challenges for entrepreneurs in these markets. Then, it proposes an open-source technology approach to build a transnational QRS assurance system. Further research is needed to determine whether and how open-source technology could enable an easy-to-use, effective, and affordable QRS system for health care devices in emerging markets.

8.1 Introduction

In 2010, at Unite for Sight's Global Health and Innovation conference, I attended a session that introduced an award-winning neonatal incubator, NeoNurture (Zenios et al. 2012). As a product designer, I was in awe of the incubator's brilliant design. Referred to as "appropriate technology," these products meet the unique conditions of the low-income markets they serve at an appropriate price. Typically, in emerging markets, a neonatal incubator would be donated from a developed market. Parts would break due to frequent power fluctuations; with no access to spare parts for these foreign-made, expensive machines, the entire device would be discarded. NeoNurture was a low-cost neonatal incubator made entirely from used car parts.

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S. Hostettler et al. (eds.), *Technologies for Development*,
DOI 10.1007/978-3-319-16247-8_8

Thus, if a part broke, the machine could easily be repaired locally and could continue to be used to save the lives of newborn children.

Bioethics is a discipline at the intersection of medicine, law, and ethics that addresses the implications of new technology on society and informs the way new technology is developed, particularly with regard to testing with human subjects. As a bioethicist, I wondered who assures the safety of appropriate technology devices in emerging markets? What kind of quality controls would be needed for a locally manufactured and repaired device? Who monitors the reliability of such a device over time?

These questions returned in 2011 at Oxford's Emerge Conference for Social Entrepreneurs. I heard Jane Chen, the co-founder of Embrace, speak about their experience developing a neonatal sleeping bag in rural India (WHO 2012). I learned that for many health care entrepreneurs in emerging markets, it is unclear how to assure quality and safety of medical devices. They face the challenging question of whose standards to follow: International Standards Organization (ISO), World Health Organization (WHO), United States Food and Drug Administration (FDA), Conformité Européene (CE) or none (if not required)?

With a professional background as a bioethicist, product designer, and social entrepreneur, I initiated this preliminary study to identify the safety issues of medical devices designed for deployment in low- and middle-income markets. This paper presents findings from interviews with multiple stakeholders on quality, reliability, and safety (QRS) issues for medical devices in emerging markets. The paper begins with an overview of the traditional device development process, identifies changing market forces that impact device development and synthesizes multiple stakeholder perspectives on QRS issues. Then, it highlights opportunities to meet QRS challenges that product designers currently face. Finally, it proposes an open-source solution to assure QRS in emerging markets and identifies key issues to be addressed for an open-source QRS system.

8.2 Methods

Forty interviews were conducted in person and via Skype with multiple stakeholders from India, Southern Africa, Europe/UK, and North America. Interview questions were open and qualitative. Questions were focused on barriers for low-cost devices to reach their intended customers, experiences assuring QRS for medical devices, and opinions about the idea of an open-source solution to assure QRS.

8.3 Results

Interviews confirmed the absence of a uniform system to assure the QRS of health care devices in emerging markets. Perspectives on how to navigate this systems level gap varied widely. Interviews were not in sufficient quantity to yield statistically valid conclusions. Results are reported in a synthesized narrative that reflects the range of views encountered.

8.3.1 Health Care Product Development

Medical device development is a burgeoning industry. Globally, QRS assurance of devices varies by country. In established markets, government regulatory systems, such as the FDA, oversee and monitor medical device development. Although considered a "gold standard," the FDA has been criticized for stifling innovation with prohibitively expensive processes and for failing its safety objective (Zuckerman et al. 2011). Some governments may expedite approval of medical devices previously approved by the FDA, or they may follow other guidelines, such as the WHO (Emergo Group n.d.). Finally, some health ministries that lack a systematic approach to address device safety may arbitrarily approve a device based on factors, such as financial compensation, rather than the results of safety evaluation. The lack of a standardized approach to safety evaluation across low- and middle-income markets creates economic uncertainty for entrepreneurs and funders as well as clinical uncertainty for clinicians and patients.

Historically, most health technology was designed in developed markets where testing and manufacturing fall under regulatory oversight, such as the FDA. Following regulatory approval and deployment into the marketplace, these products would be donated to lower income markets funded by philanthropy, gifted as hospitals acquired newer technology, and/or purchased by the governments of these markets.

8.3.2 A Changing Landscape

New Markets In recent years, there has been a shift to develop products within and for low- and middle-income markets. This shift arises from the recognition that the most significant global economic growth potential lies in the rising middle class of emerging markets and from the scale of four billion people who live on less than US$2 per day, often referred to as the Bottom of the Pyramid (BoP). The influx of capital targeting this market for impact investment has grown from US$8 billion in 2012 to a projected US$12.7 billion in 2014 (Saltuk et al. 2013).

Staggering health care costs in established markets have prompted people to seek "frugal innovations" (low-cost inventions designed by and for low-income countries). In more established markets, these frugal innovations have the potential to serve as "affordable technology" solutions (Zeschky et al. 2011). Yet frugal innovations lack a trusted way to demonstrate their QRS other than through the FDA, which then raises their cost, making them unaffordable devices.

New Sources of Capital Among those who fund health care products in low- and middle-income markets, new players have emerged. A growing trend away from traditional development that gives aid by donations has prompted more funding for empowerment-focused economic development. For example, social entrepreneurship encourages new businesses to solve local social impact issues with revenue generating business models (Yunus 2011). As a result, health care companies focused on the health needs within emerging markets are increasing.

New types of funders include venture philanthropists (philanthropists who seed economic growth in an untested or emerging market by providing the initial investment in high-risk areas with no expectation for return on investment), patient capital (investors who seek to invest in social impact opportunities with the expectation of a lower return on investment after a longer time trajectory), and impact investors (capital investors who seek to have both social impact and timely financial return on investment). In addition, crowd-funding platforms enable direct funding for device development from non-traditional sources. These new types of funders may have varying degrees of awareness and concern about devices developed in environments without QRS oversight.

New Approaches to Product Development A recent trend toward user/human-centered design has improved health care devices designed to meet the rugged and variable conditions of emerging markets (IDEO.org 2012). These new low-cost products often come from academic settings, where student projects identify appropriate technology solutions to solve health challenges. Though technically robust, these prototype solutions often struggle to reach intended markets due to barriers to financing, manufacturing, and distribution (Larson 2014; Prestero 2014).

Radical innovation in the mechanisms and methods for design and manufacture are changing medical device development. Patient innovation spreads products designed by patients, while codesign recognizes patients/users as partners in an iterative approach to product design. Moreover, open hardware (Pearce and Mushtaq 2009) and open design (Balka et al. 2009) empower local manufacturing by providing design specifications for users to modify and adapt. The rise of 3D printing allows hyper local manufacturing of an object on demand (Wohlers 2008). These grassroots, iterative and open approaches do not fit into the traditional regulatory process that approves finished products.

8.3.3 Stakeholder Perspectives on the Current State of QRS Affairs

Perspectives: Product Developers and Entrepreneurs Health care product designers and entrepreneurs recognized this gap in oversight for their products. For US-based entrepreneurs, many expressed concerns related to cost pressures and the belief that any efforts to address quality and safety would take scarce resources from constrained product development budgets. Perspectives included: “we’re under so much pressure to demonstrate that we have an idea that can work in order to secure more funding before we even think about assuring quality and safety”; “we are all too underfunded in this market to do anything like the regulatory approach”; “we’ll put the products on the market and show that they work”; “it’s better than what they have now, which is nothing”; “I never considered on whom the prototypes would be tested. We leave it up to the local doctors; they know their patients”; “open design allows for people to adapt the device to their needs; we can’t monitor quality, reliability or safety once it’s released”; “in these markets, consent is dubious; if you ask people, they will always say yes; they have no other options”; and “this is highly problematic and distressing; we don’t know whose standards to follow.” Entrepreneurs have adopted varying strategies from doing nothing to pursuing a hybrid approach that sought FDA approval for a high-cost model in established markets in order to subsidize a low-cost model.

Health care product designers from the United Kingdom, Canada and Europe consistently viewed the QRS gap as a problem. Interestingly, health care entrepreneurs based in emerging markets were the most concerned; many expressed a moral obligation to society and product users to do more than required. Some entrepreneurs chose to follow FDA guidelines, even though it did not serve their economic interests. Emerging market-based entrepreneurs expressed a need for context-appropriate, effective, and affordable solutions to assure QRS.

Perspectives: Funders and Impact Investors Interviews with impact investors and philanthropic funders yielded a range of perspectives. One health care portfolio manager from an impact investment fund was unaware of the QRS gap. Another device portfolio manager from an impact investment fund reported that it provides funding for its portfolio companies in emerging markets to fulfill FDA requirements regardless of whether the products are intended for US markets. Some funders felt that, when nothing was required, additional efforts to assure safety would be unnecessary and that money would be better spent on direct outcomes. Additionally, there was concern that unless a system was acceptable across several countries, it would not be a worthwhile use of funds. Both a funder and an entrepreneur expressed the fear that, if no one else takes these extra steps, then the time and cost put into safety assurance could put the enterprise at a competitive disadvantage. While there was interest to see an alternative approach to QRS for emerging markets, they wanted to see a pilot with adoption across multiple markets before they would financially support their portfolio companies to participate.

Perspectives: Ecosystem Stakeholders Interviews with ecosystem stakeholders included corporate device product managers, device regulatory consultants, and incubators that support new enterprises. Multiple interviewees noted that low-cost devices struggle to gain market access because they have small margins. Thus, there is little economic incentive for government interests that facilitate market entry to allow them access. Furthermore, requirements may be altered to increase money spent in the process of securing market access. Frequently expressed was the concern that products are being tested in low-income communities under conditions that may not comply with established market standards.

Perspectives: Clinicians Interviews with clinicians provided the insight that, while new experimental products may be available, unless there is research that demonstrates clinical efficacy, it is unlikely that a new product will be used. For widespread adoption of new technology, such as devices and mHealth apps, clinical effectiveness research and integration into clinical training environments will remain necessary.

However, lower level care workers, such as community health care workers (CHCW) who often provide front-line care in rural emerging markets, were eager for new technology, such as mHealth apps, to support their care efforts. Interviews with CHCWs in rural South Africa revealed preference for and deference toward new technology; namely, an mHealth app that would enhance their diagnostic abilities (Karlen and Ettinger 2013). CHCWs trusted that, if given a device for use in the field, their employer would evaluate and assure the QRS of new technology prior to issuing it to them.

Perspectives: Patients Interviews with patients in emerging markets revealed that people have a traditionally deferential relationship to care providers. Access to care is difficult. People only go to a health professional because they are very sick. In this vulnerable state, patients do not question the recommendations of providers. Further, in many low- and middle-income countries, patients do not have access to legal systems that protect consumer rights by holding faulty device makers accountable. Given these conditions, putting the burden on patients to question whether a device is experimental or safe is unreasonable.

8.3.4 Synthesis: Stakeholders in the Emerging Markets

Devices designed for deployment in emerging markets face many challenges from design through distribution (Larson 2014). From these stakeholder perspectives, the absence of a consistent system for safety assurance is clearly a pain point. In emerging markets, device funders may not be externally obligated to follow standard approaches to assure safety for their device portfolios, and only some may elect to fund their portfolios to assure device safety. To show that products work by putting them on the market without rigorously monitoring for safety outcomes is problematic. This approach turns all consumers into human research subjects and runs the risk that only successes will be identified and failures may be ignored. History reveals that the protection of human subjects in testing new products is imperative (Coleman et al. 2005). While the opportunity to deliver advances in medicine to those without access to care is compelling, *something is only better than nothing when that something is delivered in a way that respects human dignity.*

8.4 Key Issues to Address in the Current Context

The stakeholder interviews revealed these needs in the current market:

- Flexible yet standardized, transnational approach to assure the reliability and safety of devices manufactured for/in emerging markets.
- Flexible yet credible systems that provide quality assurance for open hardware, open design, 3D printing, and locally manufactured products.
- Easy-to-use, affordable, and efficient methods to guide responsible testing for prototype, pilot, and small-scale studies.
- Easy-to-use, affordable, and efficient methods to protect privacy and to assure consent for health data in the context of open data initiatives.
- Credible, affordable systems for frugal innovations, patient innovations, and makers to demonstrate safety to gain access to regulated markets.

8.5 The Timing for a New, Open Approach to QRS

Recent shifts in market forces suggest that the time may be ripe for a new approach to assuring QRS for medical devices. An open-source approach based on transparency and participatory governance could enable pooling limited resources to build a robust, transnational QRS assurance system that would leapfrog current legacy approaches and bridge the competing interests of innovation and regulation.

An Open-source Solution Open source means that the source code, the foundational structure of how something works, is openly available without proprietary conditions for use and without any restrictions on subsequent use (Open Source Initiative 2005). Defined by the type of open-source license selected, open-source projects empower people to collaborate on the development of a shared resource, enable people to improve the resource, and create a resource that is freely and openly available for use, modification, and repurposing. The transparency of open-source methods enables systems to be readily able and/or adapted to work with other systems (interoperability). The World Wide Web is enabled by W3C, a global consortium of technology stakeholders who understand the shared value in building a digital highway for information and commerce and who collaborate to develop standardized protocols for interoperable technologies (specifications, guidelines, software, tools). Similarly, collaboration by diverse device stakeholders in emerging markets to build an open-source QRS system would realize their shared interest to develop an effective and affordable way to assure QRS. An open-source QRS system could be a highway for health care innovations on the journey from research through deployment to gain access to markets while assuring safety.

Open-source Tools for Data Capture An open-source approach would mean that the basic building blocks for the QRS data monitoring system would be accessible to everyone. Developing the tools (specifications, hardware, software, and methods) needed to capture QRS data from diverse devices through open-source collaboration could enable affordable, flexible ways to capture and monitor QRS data. These open-source tools could be updated, modified, and expanded in a dynamic, participatory, and responsive manner. These open-source tools would send data directly to an open-source QRS data monitoring system.

Private Data Monitoring with an Opt-in Open Data Option There remains a high degree of sensitivity around product data and concern about showing failures. While the software system for data monitoring would be open-source to enhance interoperability, the data collected could remain private. An opt-in open data system could operate like GitHub, which is a storage company for software code. For GitHub users, one can store the code for open-source projects for free, while one pays for storage of private data (i.e., proprietary code). Thus, an opt-in open data monitoring system would give product makers a choice whether to make their QRS data open to the public. Even if an enterprise would choose to keep its data private, the data would be in a standardized format that could be evaluated and certified by independent auditors.

Real-time Data Capacity Building For this kind of open-source QRS system to be effective, it will require the capacity to monitor and analyze data in (near) real time. This approach could shift oversight from closed government systems to public–private partnerships; for example, higher educational institutions could provide real-time data monitoring services to subsidize education costs while training a new generation to develop open data skills. Thus, participation in an open-source QRS system could be a catalyst to foster technical capacity building in emerging markets.

Issues to be Addressed To realize this vision, the following questions need to be addressed:

1. What are the technically feasible ways to enable device makers to efficiently capture QRS data?
2. What are the financially viable ways to build an open data monitoring system that could serve as a global resource for QRS assurance?
3. How could a system leverage open-source tools to make it easy-to-use, effective and affordable to capture QRS data?
4. How could this approach build local skills and capacity to maintain and evaluate QRS data?
5. What type of incentive structure is needed to build this resource?
6. Will governments collaborate on a global strategy to assure QRS for health care devices in emerging markets?

8.6 Conclusion

There are critical systemic gaps in assuring the QRS of health care devices designed for deployment in low- and middle-income countries. Changing conditions necessitate developing new approaches to assure QRS for medical devices in emerging markets. There is an opportunity for further research to determine how an open technology approach to address QRS could enable an easy-to-use, effective, and affordable pathway for the responsible deployment of health care devices in emerging markets.

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Chapter 9
Solar Water Heating System Codesign and Do-It-Yourself Approach for Appropriate Technology Diffusion: The Médina Case Study (Dakar, Senegal)

Riccardo Mereu, Tomaso Amati, Lorenzo Mattarolo, Irene Bengo, Claudio di Benedetto and Ombretta Pin

Abstract In order to develop an effective method for appropriate technology diffusion, as in the solar water heater (SWH) case, the technical aspects (appropriate technology) and the planning aspects (stakeholders participation, training, and skills transfer, etc.) are both fundamental. Appropriate technologies must always take into consideration many aspects beyond the purely technical so that they can provide beneficial social, economic, and environmental impacts on the local context. This paper examines a multi-stakeholder participative approach that is focused on SWH technology diffusion and application. The integration of multiple stakeholder roles in the local context has been proposed and applied to the "Centro di Formazione Médina" (CdF Médina) or the "Médina Training Center" project and extended to the Médina neighborhood in Dakar (Senegal). The introduction of a codesign method involving engineers, engineering students, local stakeholders, and migrants, coupled with the Do-It-Yourself (DIY) technique, has been tested and recently implemented locally to permit the start-up phase of diffusion and local repeatability among trained artisans. Furthermore, with the involvement of local partners, stakeholders, and Senegalese migrants, the idea of creating a local and artisanal enterprise of SWHs has been developed, and a feasibility analysis has been carried out.

9.1 Hot Water Needs and Solar Water Heater Technology

Energy access is strongly linked and interconnected to environmental, economic, and social sustainability issues at both global and local levels. This role has been recently highlighted through different programs and initiatives such as the Sustainable Energy

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S. Hostettler et al. (eds.), *Technologies for Development*,
DOI 10.1007/978-3-319-16247-8_9

for All UN program (SE4A 2011) and the Sustainable Development Goals discussed in Rio+20 (SDG 2012). Access to energy is, indeed, not guaranteed for billions of people worldwide, and the way most of the energy is currently produced and used is not sustainable, thus increasing the need to have clean, efficient, affordable, and reliable modern energy, especially in developing countries (DC) and emerging countries (EC) where specific policies are often not implemented (AGECC 2010; Brew-Hammond 2010).

The use of renewable energies into the actual mix, especially for distributed generation in rural or limited energy access areas, has become an important supply method promoted by both local and international institutions and organizations in order to satisfy these requirements. Nevertheless, the intermittent nature of some renewable sources requires the development of specific energy system designs, while even combining renewable technologies with traditional ones in order to guarantee the reliability of the system and the supply of energy (Mandelli and Mereu 2013).

In this framework, both the electricity supply and the use of modern sources for cooking, heating, and lighting purposes are deeply investigated and supported in order to achieve a sustainable production system that limits the use of traditional biomass and oil (Mapelli and Mungwe 2013).

Among the energy needs mentioned above, hot water supply is not considered a basic need in many DC due to their warm climates, and solar water heater (SWH) use is not considered the ideal technology to enhance the living conditions of the poor population in these contexts (Langniß and Ince 2004). Despite that, hot water is increasingly regarded as a fundamental aspect of modern hygienic and healthy life in contemporary societies and, in some cases, has a key role in artisanal productive processes, thus incentivizing the demand. Furthermore, SWH actually represents an economic competitive alternative in countries with high energy costs and sufficient irradiation, therefore contributing to the introduction of possibilities for sustainable socioeconomic development (Sitzmann and Langenbruck 2003). For these reasons, many representatives of the international community believe that the SWH system is one of the most simple yet effective renewable energy technologies, which is characterized by the ability to be constructed using locally available materials by technicians without high expertise and skill (Milton 2007).

From the environmental, social, and health (i.e., local pollution) viewpoint, SWH systems reduce dependence on conventional water heating fuels such as fuelwood, propane, or fossil fuels that provide power for electric water heating systems. From a technological viewpoint, SHW systems are characterized by different typologies of collector, layout, and circulation systems. All these characteristics obviously influence the performance, technological complexity, and cost of the installed SWH system (Vanek and Albreight 2008), and the choice of the most adapted configuration is based on the analysis of the specific context.

As mentioned above, hot water supply is not a basic demand in many countries because of their warm climates, and as long as the supply of more essential goods and services is insufficient, the supply of hot water is regarded as a luxury (McEneely 2000). This is confirmed by the main use of SWH in Africa by high-income households, institutions, and large commercial establishments such as hotels and game lodges (Karekezi 2002). SWHs can be used as complementary systems in clinics, laundries, food treatment (vegetables, meat, milk, etc.), textile industries, etc.

Large worldwide penetration has occurred in some DCs, and projects on SWHs have already shown successful implementation and stable market conditions as in Zimbabwe (Weiss and Schwarzlmüller 2002) and Puerto Rico (Headley 2000). Another example is the Botswana experience in terms of the role of the quality of the installation. The project shows that even a good SWH product, when installed incorrectly, cannot work. As a result, the Botswana Bureau of Standards has developed a test method to check SWH installations on site (GEF 2005).

The aspects highlighted above show that SHW system diffusion actually requires an effort to bring the technology to an economical sustainable level (reduced costs), social role (diffusion of its availability and definition of the right target), and local technological sustainability (presence of local skills).

9.2 Design and Participative Method

An appropriate technology can be seen as one that evolves or is developed in response to a particular set of needs, in accordance with prevailing circumstances, and has been developed or adopted as the result of a rational process of decision-making with the vital participation of all the stakeholders during all the processes (Practical Action 2012). Hence, appropriate technologies must primarily enhance human capabilities through technology advancement and economic development (UNDP 2005) and achieve a social transformation (Garniati et al. 2014). Considering the characteristics of the appropriate technology mentioned above, and reported by Schumacher (1973), SWH can be evaluated as a good candidate. In fact, an SWH can be produced locally with raw materials and does not require high skills. Moreover, it presents positive environmental impacts with no pollutants or CO_2 emissions, it can be adapted to different locations with different boundary conditions, and its small scale and modularity permit its use by individual families or small groups of families.

SWH technology is further characterized by the opportunity for building by a Do-It-Yourself (DIY) approach that is labor-intensive but more productive than many other traditional processes. This approach offers the opportunity for local people to get involved in the processes of change and innovation and the use and development of the technology in small villages or small laboratories. In accordance with the context characteristics, the SWH can be designed with different layout complexities and materials that add to different solutions and costs. Though appropriate technology has been historically considered to consist more of elementary techniques that do not prioritize growth (Kaplinski 2011), the SWH DIY approach attempts to overcome this vision, thus also creating economical values within the society through the opportunity to activate small artisanal enterprises of SWH production. In this case, the repeatability of the technology becomes a feature that is even more important in the process of diffusion of the same. The possibility to start income-generating activities of artisanal construction of SWH interfacing with the market implies in itself an even stronger analysis of the local context. The identification of the target beneficiaries, their needs and their resources, and the involvement of all local actors and their desires become, in fact, essential and require a thorough participatory process.

In order to ensure the sustainability of the project's activities and the repeatability of its results, a participative methodology is essential throughout the project's duration. In a technology transfer project, the correct individuation of the community needs and the available resources is essential in order to define the most appropriate solution, and it requires a careful involvement of all stakeholders. It must be understood that the technology integrates itself in a cultural and social context with specific environmental and economic conditions that influence and are influenced at the same level by the new conditions. If the aim is to make the communities autonomous, self-organized and independent, and/or guarantee the repeatability of the impacts, technology and innovation alone are not sufficient, but must be driven by human factors and be coupled with the principle of participation and direct community involvement.

The entire process is schematically reported in Fig. 9.1, which indicates the participative methodology in the energy access framework. The development technology process is carried out by different stakeholders—locals, migrants, engineers—each of whom brings personal background and competencies as inputs to the decision-making process. As in the case of the SWH development with the DIY approach, the participative context analysis supports the development of an appropriate technology with innovative solutions and real transfer skills.

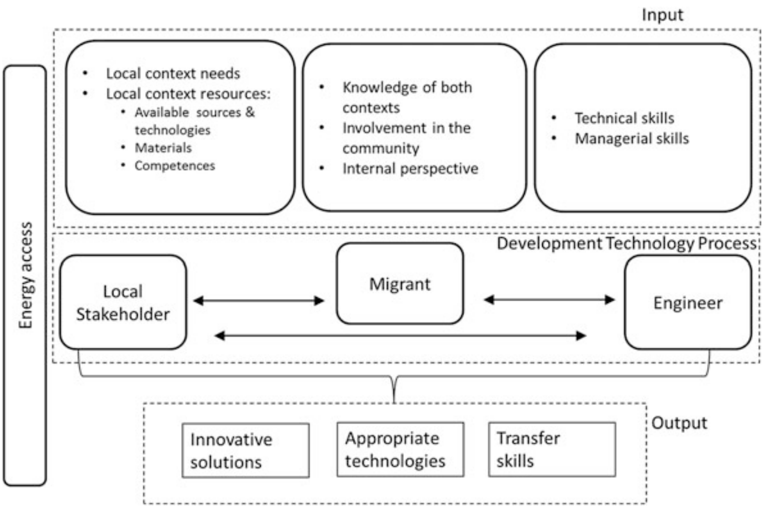

Fig. 9.1 Participative energy access framework

The figure of the engineer has to focus not only on the appropriate technology and innovation but also on human promotion. In this framework, the facilitator has a key role in the participation process. His or her main function is to facilitate communication between the involved parties; this includes explaining the scope of the debate and guaranteeing that it will not be polarized or monopolized, and providing help with difficulties related to the use of technical language (Ramirez et al. 2010).

In this process, the migrants can represent a key figure and serve as the bridge between local and external contexts to integrate the figure of the facilitator and aid worker. The migrant's role in this kind of project represents an extension of its classical role in migration and development projects, which can be considered as a field between cooperation and local development. The aim of migration and development processes is not only to promote development in countries of origin but to also create synergies between migrants' participation in cooperation projects and their integration in countries of destination. For this reason, migration and development strategies are innovative policies to foster trans-local spaces of solidarity where migrants play a key role as links between governments, civil society, and populations, both in countries of origin and destination (Acebillo-Baqué and Østergaard-Nielsen 2011). In addition to remittances and other types of financial transfers, migrants stimulate the development of countries of origin and destination with the transfer of know-how and knowledge. In fact, people, as they move, take with them ideas and knowledge and acquire new skills and ideas while in abroad (IOM 2010). While the Declaration of the High-level Dialogue on International Migration and Development states that "emigration is not an alternative to accelerated development efforts at home, but mobility can facilitate access to ideas, knowledge and resources that can complement and in some cases enhance progress" (UN 2013), migrants can propose themselves as active stakeholders in North–South development projects because of the context knowledge of both countries and can assume the fundamental role of dialogue facilitators during the analysis phase and in the problem-solving and decision-making steps.

9.3 The Médina (Dakar, Senegal) Case Study

Presented here are the application of the approach described in Sect. 9.2 and related results carried out in the project "Centro di Formazione Médina" (CdF Médina) or "Médina Training Centre" and its extension to the neighborhood of Médina in Dakar (Senegal). The process phases and roles of the involved stakeholders are highlighted and schematically shown in Fig. 9.2.

CdF Médina The project CdF Médina, which began in 2007 and was based on the Médina of Dakar (Senegal), had the purpose to improve the living, health, and economic conditions of weavers working in the sphere of fair trade, the students at the CdF Médina training center, and the community in which they operate through a

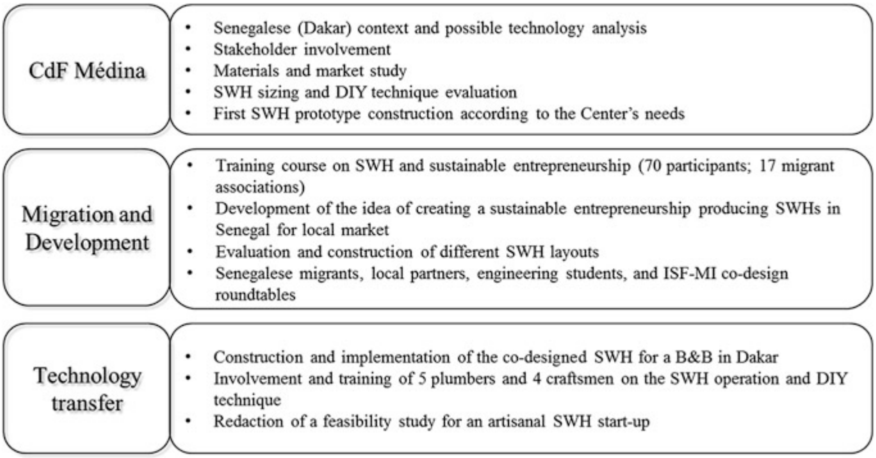

Fig. 9.2 Approach and results of the CdF Médina Project

qualifying training scheme, and real support for the concrete development of sustainable economic activities. The CdF Médina is part of the wider Senegalese textile chain that has witnessed a growing effort to enhance the national product through the promotion of organic cotton and the rediscovery of traditional techniques for weaving and fabric dyeing. The project has involved qualified partners in fair trade (Karibuny), textile craftsmanship, local nongovernmental organization (Yaakaar G. I.E and Domû Africa), and Engineering Without Borders—Milan (ISF-MI) for the technological transfer and training.

The ISF-MI role was to face and cope with the energy access issue that was present in the training center and atelier for both electricity and heat supply. Hot water for textile production (dye fixing) and for domestic use (showers, cooking, etc.), led to an analysis of the local context to determine the needs and resources, available technologies, and proper introduction of new ones into the context.

Different resources and technologies have been considered and studied in order to evaluate the most appropriate solution to guarantee good social, economic, and environmental impacts in the Center. With this aim, the preliminary design of a DIY SWH system as an alternative to previous biomass (fuelwood) and gas use has been carried out. In this phase of the project, a context analysis was carried out on the field by ISF-MI to focus on the possible craftsmen concerned in the DIY activity and on the locally available materials and skills. Local artisans have been involved and the available materials and skills have been defined. The analysis revealed the presence of good logistics to supply materials in Dakar and the presence of technical skills (welding, glass production, etc.), but at the same time, it underlined the need of the training for a not yet well-known technology. Furthermore, the same training requirement for the installation and maintenance of the SWH system emerged from the study of the local SWH commercial market, which is entirely composed of imported solutions and is still not well developed. Finally, a prototype of the DIY SWH system that fits the Center's needs has been built.

Migration and Development The activities carried out in the local context have been integrated with training courses that are focused on the topic of sustainable entrepreneurship in DC in the energy sectors. The case study of CdF Médina has been presented in the courses based on the preliminary analysis carried out by ISF-MI and local partners. The courses have been attended by 17 migrant associations from different origin countries and 32 students of Politecnico di Milano for a total of approximately 70 participants. This environment, where different cultural and technical backgrounds have been mixed, permitted the development of the theme of the SWH as a possibility of artisanal production through the DIY approach. Hence, the theme has been thoroughly analyzed and a joint planning at both the technological and managerial level has been codesigned involving Politecnico di Milano students, Senegalese migrants, and ISF-MI. In this phase, owing to the active participation of Senegalese migrants and through their contact with local associations, it has been possible to provide continuity to the idea of creating a local and artisanal enterprise of SWH panels.

The first possible beneficiaries for the SWH have been identified as tourist accommodation businesses, hospitals, clinics, laundries, textile and food production activities, and households. Consequently, they have defined the main systems' characteristics: they have to be lasting but simple, market competitive, and guarantee a good efficiency. A system with an open thermosyphon configuration and a glazed flat plate panel has been chosen in accordance with the mentioned features, materials, and resources.

Technology Transfer As an application of the previous analysis, a codesigned system has been built and implemented in a bed and breakfast (B&B) of a local cultural association in Dakar. The construction and implementation have been completed with an on-the-job training course that involved five plumbers and four craftsmen who were previously identified with the local partners. During the three-week course, both the theory of SWH and the practical implementation of the system have been treated. The implemented system cost has been approximately half of the average commercial systems present in Dakar retailers. Finally, two of the plumbers and the four craftsmen who were involved in the construction offered their availability to work together and start running a business in order to investigate the opportunity to develop an even lower cost solution for different beneficiary targets that are actually under investigation.

A feasibility analysis for the artisanal SWH entrepreneurship has been carried out. The concept of the business model developed, based on the value chain model (Porter 1985), is shown in Fig. 9.3, where the key primary and support activities of the potential artisanal enterprise are reported. In addition to this, target market segments and foreseen social impacts are presented in order to provide a more complete view of the social business idea. The artisanal enterprise will be structured in the form of a cooperative with the presence of the previously trained craftsmen to

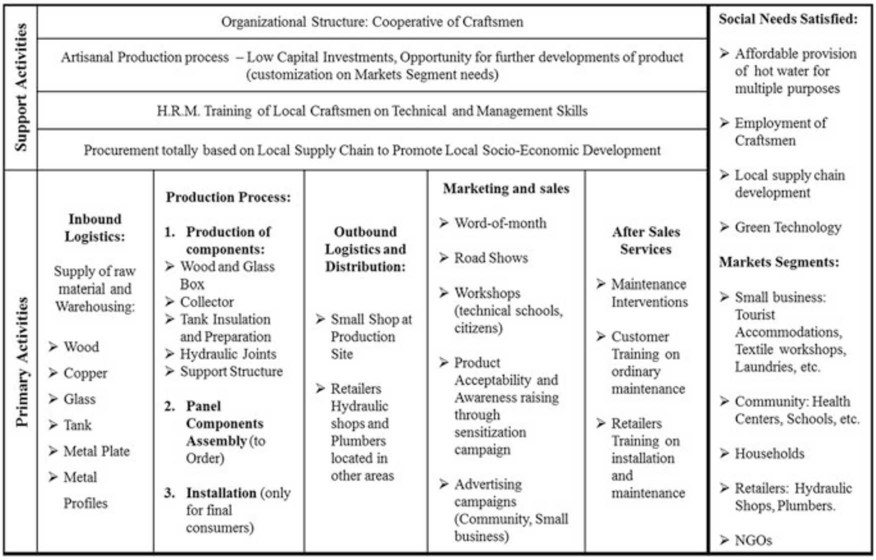

Fig. 9.3 Business model concept. Inspired by the value chain model (Porter 1985)

ensure adequate technical and management skills. The production process, comprising three phases, is totally based on the use of local manpower and materials in order to maximize local socioeconomic development.

9.4 Conclusions

The introduction of a codesign method involving engineers, engineering students, local stakeholders, and migrants, coupled with an appropriate technique (DIY), has permitted the identification and implementation of an appropriate energy system. The codesigned system has been tested and locally implemented to permit the start-up of the phase of diffusion and local repeatability among trained artisans. Furthermore, with the involvement of local partners, stakeholders, and Senegalese migrants, the idea of creating a local and artisanal enterprise of SWH panels has been developed, a detailed feasibility analysis has been created, and it will be ready for implementation in the near future. Finally, the DIY construction technique proposed in the project represents a valid example of appropriate technology where all the dimensions of sustainability are taken into account; at the same time, this approach guarantees environmental (increasing the reuse and recycling of waste materials), economic (investing in a local market where there is a constantly growing demand), and social sustainability (recognizing the value of and enhancing local skills and guaranteeing independence from external subsidies), which, coupled with entrepreneurship initiatives, can represent a means of economic development for local stakeholders.

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Chapter 10
Facilitating Adoption of a Private Sector Led Open Innovation Approach to Rural Sanitation Marketing in Bangladesh

F. Conor Riggs and Chetan Kaanadka

Abstract In rural Bangladesh, the need for wider distribution of accessible, customer-oriented improved sanitation facilities for low-income communities has never been greater. Yet the market for affordable sanitation products in rural Bangladesh is fundamentally characterized by a lack of formal commercial linkages between sanitation entrepreneurs (SE) and commercial lead firms (LF) with scalable, sustainable, and dynamic products and business models. Encouraging LFs to adopt an open innovation approach by developing business models that generate a "living lab" environment represents a promising direction to increase the capacity of SEs to provide improved products and services to low-income consumers in a sustainable manner. Utilizing a Human-Centered Design (HCD) methodology, the Bangladesh SanMark Pilot (BSMP) project (2012–2014) implemented by iDE aimed to develop a living lab outcome for LFs and SEs in Rajshahi District, Bangladesh that was underpinned by business model that would encourage LFs to actively engage with SEs in Bangladesh for the design and development of context-appropriate sanitation products and services. By its conclusion, the project supported the development of an upgradeable latrine product that reached over 28,000 people in 9 months. The positive feedback loop created through this "living lab business model" encouraged the LF to manufacture a mass-producible version of the latrine product from 2015, channeled through a fully commercial business model that formally links SEs to the large-scale marketing and distribution infrastructure of the LF as retailers that is grounded in continual interaction with formerly disconnected SEs and local government institutions.

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S. Hostettler et al. (eds.), *Technologies for Development*,
DOI 10.1007/978-3-319-16247-8_10

10.1 Background

Universal access to hygienic sanitation products and services represents a public health challenge of global proportions. Worldwide 2.5 billion people lack sustainable access to improved sanitation, and 1.1 billion still practice open defecation. In Bangladesh, the past decade has witnessed an astounding growth in accessibility to hygienic latrines in rural areas (WHO/UNICEF 2013). Fuelled by the determined efforts by the Government of Bangladesh (GOB) through its *Sanitation for All* campaign (a Community Led Total Sanitation (CLTS) movement) and the development sector's diffusion of motivational campaigns and subsidized basic sanitation facilities, the number of latrines in rural Bangladesh has increased by leaps and bounds, subsequently brining down rates of open defecation (Devine and Kullman 2011). However, the low levels of hygienic latrine provision in rural Bangladesh casts a shadow on the celebrated success story of the subsidy-led CLTS model, effectively limiting its impact. Although there exists a strong willingness to adopt hygienic latrines, existing latrine market is incapable of matching the demand. The rural population of Bangladesh comprises of 71 % of the total population, out of which 94 % or approximately 93.4 million people are latrine owners. However, 47 % of these latrines are unimproved, unhygienic latrines, representing a population of 5.8 million households, or 40.7 million persons. Standard hygienic or "improved" latrines as defined by the Joint Monitoring Program (JMP) include a pit latrine with a hygienic slab, or a pour flush toilet or a ventilated improved pit (VIP) latrine (WHO/UNICEF 2013).

Furthermore, nearly 96 % of rural households in Bangladesh pay for their own sanitation services, yet many struggle to access enough finance to purchase a hygienic latrine that meets their physical and social needs. Additionally, general awareness on product features and benefits, particularly pertaining to hygiene is low. Many consumers are required to develop their own version of a hygienic latrine using piecemeal components. On the supply side, the majority of latrine producers have limited and rudimentary product offerings, usually promoted by the subsidy-led CLTS program, consistent with international research findings on small-scale sanitation service provision (Gero et al. 2013).

Analysis indicates that the market for affordable sanitation products in rural Bangladesh is fundamentally characterized by a lack of formal commercial linkages between sanitation entrepreneurs (SE) and commercial firms with scalable, sustainable, and dynamic products and business models, or lead firms (LF). Relationships between SEs and LFs are typically limited to the purchase of latrine inputs.[1] While a number of LFs operate through expansive dealership and retail networks throughout the country, interaction between their dealers/retailers and SEs is confined to the procurement of inputs. The relationship between these actors results in a lack of basic supporting services access for SEs, including above the

[1]Typical latrine inputs include cement, sand, brick, paint, and plastic or ceramic latrine pans.

line marketing, sales training or credit, consistent with global findings of similar markets (Chowdhry and Kone 2012; USAID 2009; Sy et al. 2013).

These weak linkages drive relatively stagnant growth amongst SEs. Lacking access to research and development (R&D) capacity, SEs typically offer limited product options (Salter 2008; Sy et al. 2013). Although technically proven sanitation technologies are abundant and well catalogued, SEs have no access to such knowledge outside the products promoted by GOB and the development sector, leaving low-income rural consumers with affordable but unhygienic direct pit latrines or desirable but unaffordable improved latrines. Moreover, SEs often have low incentive to produce quality products, and often compromise with the durability of the concrete components to improve their profit margins from low-income customers. SEs also have poor marketing capabilities, leading to sluggish penetration of low-income customer segments.

10.2 Purpose

Underlying these market dynamics is the fact that the majority of LFs in Bangladesh employ a *closed innovation approach* to rural sanitation that discourages intensified engagement with SEs. LFs typically adhere to Chesbrough's (2003) notion that successful innovation requires control, and that innovation is best accomplished by product development efforts limited to the confines of the firm's internal resources and structures. As a result, the novelty of resulting product offerings largely emanates from the firm's existing market intelligence and R&D capabilities. Yet escalating competition and shorter product life cycles indicate that a closed innovation strategy is relatively costly, slow, and generates suboptimal returns on investment (Vanhaverbeke et al. 2008). Such conclusions have contributed to the emergence of the open innovation approach.

Chesbrough (2003) defines *open innovation* as "the use of purposive inflows and outflows of knowledge to increase the speed of internal innovation processes, and expand the markets for external use of innovation, respectively." In direct opposition to the closed innovation approach, open innovation rests on the idea of the firm leveraging widely distributed knowledge and resources across a diverse group of internal and external stakeholders. In an open innovation environment, users transform from passive content consumers to active participants in producing content, solving technical problems, and contributing to development of innovations (Følstad 2008; Ståhlbröst 2008).

Taking an open innovation approach requires the firm to embrace the notion that innovative ideas do not necessarily need to reside within the organization itself, and that research does not need to originate from within the walls of the firm for it to realize profitable opportunities. This approach does not simply denote a slackening of control while hoping for the best (Boudreau and Lakhani 2009). Rather, the open innovation approach advises the firm to develop mechanisms that govern, shape, direct and, if necessary, constrain external innovators in ways that enable the firm to access outside ideas, relationships, and processes. Accordingly, it has become increasingly essential for LFs to identify and tap into the knowledge of stakeholders outside the organization (Chesbrough 2003).

The *living lab* concept represents a promising direction in which to apply an open innovation approach to practical commercial settings. The living lab concept emerged in 2000 (Markopoulos and Rauterberg 2000) when William J. Mitchell proposed to move various types of research from laboratories to in vivo settings for improved monitoring of users' responses to, and interactions with, "innovative" products under development. The European Network describes a living lab as "an open innovation environment in real-life settings in which user-driven innovation is the co-creation process for new services, products, and societal infrastructures. Living Labs encompass societal and technological dimensions simultaneously in a business-citizens government- academia partnership." Similarly, Holst et al. (2010) contend that a living lab "a user-centric innovation milieu built on everyday practice and research, with an approach that facilitates user influence in open and distributed innovation processes engaging all relevant partners in real-life contexts, aiming to create sustainable values" (Bergvall-Kåreborn et al. 2009).

With approximately 100 million rural Bangladeshis requiring improved sanitation facilities, yet weak linkages between LFs with the capacities to act on innovative ideas and the SEs who bridge the "last mile" to the consumer, the need for local and international LFs to operate living labs for wider distribution of accessible, customer-oriented improved sanitation facilities has never been greater. Accordingly, the Bangladesh SanMark Pilot (BSMP) project, funded by the Swiss Agency for Development and Cooperation (SDC) and Water and Sanitation Program (WSP), supported by UNICEF, and implemented by International Development Enterprises (iDE), was introduced in 2012 to facilitate a viable market system for a new improved, desirable, and affordable latrine, underpinned by private sector led distribution and marketing and localized public–private partnership (PPP) platforms. The project was implemented in the Durgapur, Mohanpur, and Bagmara *upazilas* (subdistricts) of Rajshahi District, Bangladesh from January 2012 through April 2014.

10.3 Method

In practice, BSMP aimed to develop a living lab outcome for LFs and SEs underpinned by a business model that would encourage LFs to actively engage with SEs in Bangladesh for the design and development of context-appropriate sanitation products and services. The project utilized the Human-Centered Design (HCD) approach to encourage living lab conditions between SEs and LFs, including active participation of relevant stakeholders and end users to gain a deep understanding of the context and then develop and test appropriate solutions. HCD, which originally emerged out of interactive computing systems but now represents a promising means to address development challenges including affordable sanitation (Narracott and Norman 2011; Pedi et al. 2012; Rosenboom et al. 2011), is founded on the necessity for interactive processes, an explicit understating of the end user, and a multidisciplinary approach, both with skills and perspectives (IDEO 2011). Through this process, BSMP demonstrated to a prominent LF the influence of collective participation of the community in guiding the product design and business innovations to suit their needs and requirements.

BSMP interventions were implemented in four distinct phases: (1) preparation, (2) research and design, (3) prototyping and testing, and (4) business model development. The stakeholders fluidly participated throughout all the phases of the project. In each phase, various stakeholders from both private and public partners in the global and local spheres expanded to create a multistakeholder network through which information, influence, money and material began to flow, as illustrated in Fig. 10.1. To bring about multistakeholder participation in line with an open innovation approach, it was essential to build a collaborative work environment, tailored to the context of the project areas.

The living lab environment generated by BSMP comprised of four categories or groups interacting and collaborating within and between the categories. The functions of this living lab depend on which group plays the central role in them (Arnkil et al. 2010). At each phase of the project, different players played the central role. However, BSMP played the lead role throughout the project as strategic facilitator, responsible for developing partnerships and collaborations between the various stakeholders and for guiding them through innovation development process. The roles and responsibilities played by each group of stakeholders are summarized in Table 10.1.

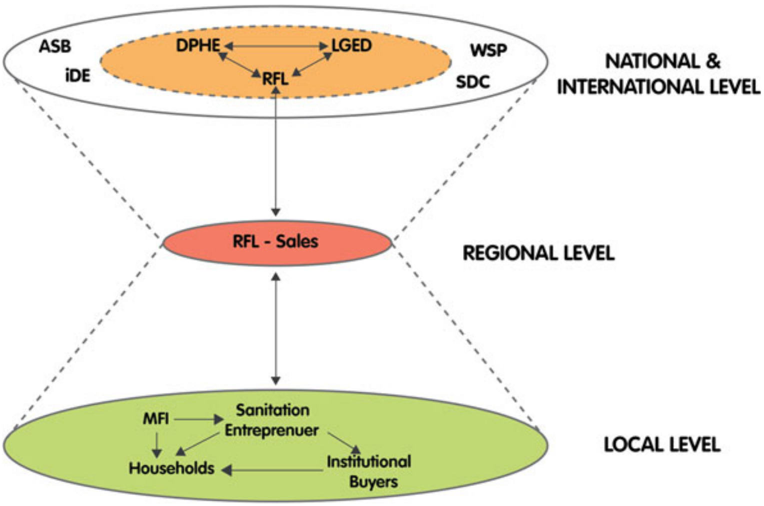

Fig. 10.1 Multi-sector stakeholder relationship mapping of the BSMP living lab

Table 10.1 Roles and responsibilities of key stakeholders within BSMP project living lab

Local community	Providing information about their needs and experiences
	Testing products and services under real use conditions and providing feedback to the other stakeholders
	Responsible for selecting the appropriate innovations that would be implemented and developed further
Lead firms	Gather information on consumer needs, desires, and aspirations
	Apply the knowledge and information gathered through research for developing the products and services
	Commercialization and delivery of products and services to the community
Government bodies	Increasing the involvement of community members
	Supporting the community, businesses, and public authorities in their innovation activities and programs by providing support funds, knowledge, expertise network, and infrastructure
	The development of public service schemes and programs to support innovation activities
Development organizations	Carry out HCD research methods and facilitate codesign and cocreation processes
	Provide support and facilitate partnership, collaboration, and cocreation process by creating platforms for mutual dialogues and decision-making between stakeholders
	Supporting and facilitating the communities, public authorities, and private lead firms to implement their respective activities based on new ideas and solutions

10.4 Results

Initially, the living lab environment piloted through BSMP facilitated innovative new product offerings for improved sanitation marketed to low-income customers. Initially, BSMP leveraged global ties between iDE and American Standard Brands (ASB) to support ASB's development of the SaTo® plastic latrine pan, an innovative new "user interface" for consumers that addresses design flaws in existing pan and trap product offerings. Through HCD research approach, it was possible to gain a robust understanding of the needs and desires of the user and other stakeholders. Based on the stakeholders' insights, ASB designed the SaTo® Pan—an improved and affordable sanitation solution—which fits into the context without requiring any radical change in user behavior, including the amount of water that is generally used to flush the toilet (<1.25 l). RFL Plastics Ltd., a national plastics manufacturer within PRAN-RFL Group, took up the mass production and marketing of the SaTo® pan in Bangladesh, resulting in over 300,000 SaTo® pans produced and distributed from April 2013 to August 2014 across 64 districts in Bangladesh.

Yet the SaTo® pan was only one of the many components of a complete toilet solution needed by the households. Insights gained through the application of the

HCD approach during prototype testing under BSMP revealed that even though SaTo® pan effectively addressed the technical design flaws in the existing pan traps used in direct pit latrines, it did not fill the aspirational gap of consumers to own an affordable offset latrine. Accordingly, the BSMP engaged both RFL and SEs through iDE's HCD process to cocreate the standardized but modular "Sanitation in a Box" (SanBox) product line. The SanBox product enables households of different income levels to purchase a quality, hygienic latrine product that enables simple conversion of direct pit toilet to offset, twin-pit toilet system. During BSMP pilot testing, SEs sold an estimated 5774 units of the first generation SanBox within 9 months, reaching an estimated 28,870 people, with a fully mass-producible version projected to sell upwards of 100,000 units annually at national scale to be introduced in 2015.

While these innovative products resulted from the living lab environment facilitated by BSMP, ensuring the sustainability of collaboration between the local LF and SEs required a new business model grounded in intensified linkages between these commercial actors, while also enabling collaborative spaces with government at the national and local levels, and end users. Accordingly, BSMP facilitated a fully commercial business model (Fig. 10.2) that formally linked SEs to the large-scale marketing and distribution infrastructure of the LF.

Under the model, the LF plays a central role in initiating communication and coordination among SEs and government actors at both the local and national level. The LF recognizes the incentive in sustaining and further developing the business

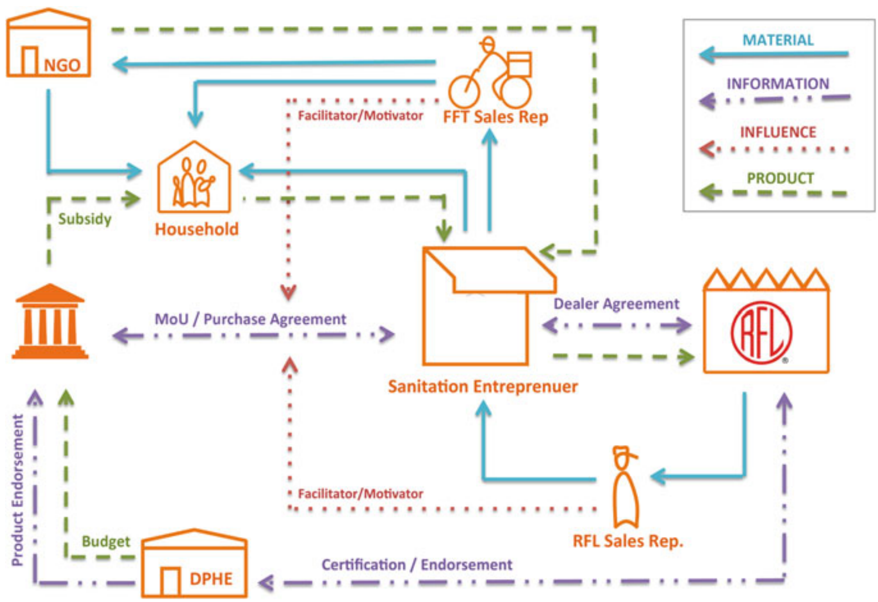

Fig. 10.2 Living lab business model facilitated by the BSMP project

model by formally upgrading the ‘SE’ to ‘Sanitation Retailers’ within their national distribution network with accordant access to dealership services including above the line marketing, credit, and skills training. In addition, the positive feedback loop created through this open innovation ecosystem has helped the LF to identify an opportunity to invest its creative capital in developing a mass-producible SanBox to enhance the product’s sustainability and scalability, resulting in the development of a reinforced business model. Furthermore, the living lab approach facilitated by BSMP has led to the creation of a PPP platform model in which the district-level marketing personnel of the LF actively marketing the SanBox to both local and national government bodies and agencies. As a result, the national government has endorsed the SanBox product; incentivizing local government institutions to procure the product through the Sanitation Retailers who formally received support from the LF.

10.5 Conclusions

Through utilization of the HCD process, BSMP facilitated the emergence of a self-sustaining and self-managing living lab environment between a large-scale commercial firm and informal, “last mile” SEs with the capability to sustain an open innovation approach to improved sanitation research and design in the future. At the project end, the local LF partner was better able to nurture product and business innovations through a continuous exchange of ideas, resources, and expertise with SEs and the public sector through a multistakeholder business model. This living lab business model was underpinned by a series of product innovations achieved by the BSMP project, including a modular latrine product that meets the diverse requirements of the market from a basic latrine to a more complex model. Furthermore, the living lab business model developed through this project has allowed the influx of innovative ideas, resources, and expertise from users, SEs and government actors to the LF, improving the firm’s ability to solve both product and service challenges directly focused on the target market.

The BSMP project provides promising evidence to support the adoption of a living lab approach for the development of rural sanitation markets characterized by LFs utilizing an open innovation approach, establishing a living lab environment in which the needs and desires of users take a driving seat in the R&D activities is paramount. To establish such an environment in a sustainable manner requires a business model that builds linkages between LFs and local service providers at the community level such as SEs, in addition to key public sector stakeholders, in order to encourage inclusive participation that results in innovative new products generating simultaneous increases in the commercial, social, and public health returns for LFs, SEs, and the low-income communities for which development projects such as BSMP are designed.

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Part IV
Medical Technologies for the Global South

Chapter 11
Medical Devices and Information Communication Technologies for the Base of the Pyramid

Zach Friedman and Walter Karlen

Abstract Providing adequate access to medical care in developing countries is a systemic and complex issue, driven by numerous challenges ranging from issues in delivery of care to broader development issues. One key issue is the lack of appropriate, low-cost devices to diagnose and treat what are often easily addressed medical conditions. The last decade has seen the development of numerous low-cost medical devices and the application of information and communication technologies. A limited number of projects, however, manage to pass the pilot testing stage and go on to achieve impact at scale. The reasons for this are multifaceted. In this paper, we discuss challenges presented by medical device markets and challenges in the development of these technologies. We argue that multidisciplinary dialogue and public–private partnerships are the essential factors that lead to the integrity and success of low-cost health systems in small and fragmented markets.

11.1 Introduction

Providing adequate access to medical care in developing countries is a systemic and complex issue, driven by numerous challenges ranging from issues in delivery of care such as a lack of trained practitioners to broader development issues such as malnutrition and poor living conditions. One key issue is the lack of appropriate, low-cost devices to diagnose and treat what are often easily addressed medical

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S. Hostettler et al. (eds.), *Technologies for Development*,
DOI 10.1007/978-3-319-16247-8_11

conditions. The last decade has seen the development of numerous low-cost medical devices and the application of information and communication technologies (ICT), often combined with health innovations on mobile phones (mHealth). A limited number of projects, however, manage to pass the pilot testing stage (Labrique et al. 2013) and go on to achieve impact at scale. The reasons for this are multifaceted. In the following paragraphs, we highlight some current challenges, addressing both challenges presented by medical device markets and challenges in the development of the technologies themselves.

11.2 Market Challenges

The medical device market for developing countries, particularly across sub-Saharan Africa and South Asia, is often described as a massive opportunity waiting to be unlocked. While there is a large future opportunity, and health care in developing countries is growing, the current market for medical devices is modest. Many countries in sub-Saharan Africa have only a few dozen hospitals with a meaningful equipment budget and, while there may be several thousand of primary care clinics in a midsized country like Kenya, these facilities have neither the funds nor the mandate to purchase equipment.

An example of this can be seen in vaccine refrigeration, a market where there is strong global attention, but a small actual market and a subsequent lack of appropriate products. The Bill & Melinda Gates Foundation (BMGF) which has funded billions of dollars of work in vaccination, reports that only 33 % of clinics in countries supported by the Global Alliance for Vaccines and Immunisation (Gavi 2013) are equipped with cold chain equipment (i.e., vaccine refrigerators), that 20 % of those facilities have nonfunctioning equipment, and as many as 20–25 % of vaccines are exposed to freezing temperatures that can reduce their efficacy (BMGF 2013). Clearly, vaccine refrigeration is an area with ample opportunity for improvement. However, while more than US$1 billion is spent annually on vaccines, spending on cold chain equipment is estimated to be only US$40 million (Gavi 2013). For large companies with the experience, expertise and resources to develop and distribute innovative, low-cost products at scale, the vaccine refrigeration market is simply too small. Top medical device manufacturers generate US$1 billion+ per year in revenue, while appliance manufacturers are larger. For multibillion dollar companies trying to drive top-line growth, a US$40 million market is not a large enough opportunity to provide business-relevant financial returns.

A second major issue is that the currently small ‘global market’ is, in fact, actually dozens of even smaller national markets. The vaccine cold chain equipment market, for example, exists across 50 countries, each having different purchasing processes, regulations, and requirements for doing business. This holds true for many recently introduced medical products including ultrasounds, infant warmers, phototherapy, and wheelchairs. Some countries purchase primarily through the national ministry of health while other countries, such as Kenya, have empowered regional governments to manage their own budgets. Needs, existing infrastructure and strategies toward equipping clinics vary across countries as well.

In the absence of major medical device manufacturers, fragmentation exists amongst suppliers, exacerbating the difficulty of penetrating medical device markets by making purchasing and servicing more challenging for the customer. To equip a primary health clinic, a facility manager needs to purchase from multiple suppliers and often devices are designed to function independently. That is, each device comes with its own ICT interface (usually its own phone or tablet), power supply, and data tracking system (if there is one). Optimization occurs at the device level rather than the facility level. The customer is left having to work with multiple suppliers to purchase and service those devices.

This fragmentation and the resulting difficulty in fully equipping facilities create an additional "chicken-and-egg" problem for new devices attempting to enter the market. Many medical conditions co-occur (e.g., HIV patients frequently need treatment for tuberculosis in addition to HIV), and the ability to treat just one condition is of limited value. Another example is that preterm infants often suffer from jaundice and require treatment with a phototherapy device. However, these infants often require treatment for several other conditions as well, and the ability to treat jaundice, without the ability to provide the full scope of care such as feeding support, external warmth, or treatment for infections, can render a facility insufficient to treat infants with jaundice. A facility that wishes to provide care for preterm infants needs to provide a whole array of complementary services, and simply having one device is of limited use.

11.3 Technology and Design Challenges

Medical devices and sensors that are established in industrialized nations' hospitals are often not adequately designed for point-of-care use in a low resource setting. Physical dimensions and power consumption prevent the direct adoption of the technology. Further, the rural setting adds tighter constraints to robustness and maximum allowable cost. Costs for maintenance, spare parts, and disposable components need to be considered. For mHealth applications, more targeted sensors for the mobile framework are needed (Kumar et al. 2013). Further, medical devices and user interfaces are traditionally designed for the medically trained experts. Medical devices and mHealth tools can easily become a burden to health workers if the solution is too technology focused (Strachan et al. 2012). It has been suggested that mobile devices should be transformed into functional job aids, which can become an additional motivating factor for technology uptake. For example, this effect was observed in a recent pilot study on implementing mHealth for maternal health monitoring in Ethiopia (Little et al. 2013). Health workers were able to develop a sense of ownership and consequently stay motivated in using and maintaining the device functionality. Therefore, we consider it important to evaluate new mHealth solutions rigorously for usability and acceptance to assure the solution is functional and aligns with cultural, societal, and institutional constraints. Attaining usability of mHealth solutions can be facilitated by user-centered and participatory design that includes users in the design process throughout all steps of product development.

Certain medical sensors, such as pulse oximeters (Karlen et al. 2011; Payne et al. 2014) or ultrasound probes have been successfully interfaced with mobile phones to monitor vital signs in remote settings. Similarly, microscopy and spectroscopy are available through mobile phone cameras (Coskun 2013). While size and power consumption have been addressed, a major challenge remains in the maintenance of quality and robustness of these systems in a challenging environment. To ensure quality, developers and engineers rely on standards. Many standards for medical devices are written and updated with companies and customers in industrialized nations in mind. This leads to overregulation in a resource-poor setting. Often, the standards are not appropriately designed for these settings and cannot be implemented cost-effectively. A shift toward a minimum requirements standard would be desirable. The risk of creating dual standards needs to be discussed more widely. The issues of data security, privacy, and confidentiality should be added to the discussion. Countries with well-established regulatory systems have made advances in providing guidelines for ICT security in health systems. We argue that further research and discussions on privacy options with mobile systems are needed, especially for resource-poor settings with different cultural backgrounds.

It is evident that data collected in a remote location by health workers with little experience and training can interfere with quality and lead to poor decisions. Despite this, very little research on quality control for ICT and mHealth data has been undertaken. We observed an increased awareness on the importance to monitor quality and adoption during the EPFL-UNESCO Conference on Technologies for Development (2014 Tech4Dev). Open data models have been suggested to improve quality and transparency of medical devices for low resource settings (Ettinger 2015, Chap. 8), as well as the analysis of recorded biomedical signals with mobile devices (Stroux and Clifford 2014). As discussed in Chap. 12 (Beratarrechea et al. 2015), it is very difficult to demonstrate evidence of interventions with randomized control trials (Philbrick 2013). The monitoring of adoption and effectiveness with data tools is one of the many opportunities that open data can provide and therefore increase confidence in technology.

Scaling up of technological solutions in developing countries is still one of the largest challenges. Appropriate methods to achieve scale-up for mHealth are often not implemented (Tomlinson 2013) as businesses or other entities experiences in at-scale delivery are often not interested in these markets (see also Sect. 11.2 on market issues). Further, since competing health system priorities can prevent the uptake of mHealth solutions into state funded health systems (WHO 2011), often the political environment, or preexisting organizational structures (Densmore 2012) can impede the widespread distribution of successfully piloted systems.

The development of biomedical devices is a multidisciplinary undertaking between engineers, developers, social entrepreneurs, health providers, patients, policy makers, and researchers from social, business, medical and basic sciences, and it is beneficial to enable the dialogue between these stakeholders early in the development process. This essential multidisciplinary dialogue as well as public–private partnerships could be the most important factor that leads to the integrity and success of health systems. As we see an increase in low-cost medical devices and a growing interest of large biomedical companies in health care technology for resource-poor settings (Leeds et al. 2015, Chap. 15), we are confident that challenges with small and fragmented markets can be resolved and the focus will shift toward implementing appropriate standards and scaling-up of robust products and markets.

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Chapter 12
Challenges of Implementing mHealth Interventions for Lifestyle Modification in Prehypertensive Subjects in Argentina, Guatemala, and Peru

Andrea Beratarrechea, Rebecca Kanter, Francisco Diez-Canseco, Ariel Fernandez, Manuel Ramirez-Zea, Jaime Miranda, Homero Martinez and Adolfo Rubinstein

Abstract The present study describes the processes related to the implementation of mHealth interventions for lifestyle modification in a randomized controlled trial conducted with prehypertensive subjects in Argentina, Guatemala, and Peru from low-resource settings. In the intervention group, participants received, during the course of a year, a monthly counseling call from a trained caller and a one-way weekly tailored short message service (SMS) to promote lifestyle modification. We evaluated reach, fidelity, dose, and attrition to assess how the intervention was implemented. 637 prehypertensives were included in the study, 321 in the control and 316 in the intervention group. Fifty-three percent were women with a mean age of 43.4 ± 8.4 years. Ninety-eight percent of the participants assigned to the mHealth arm were reached. The mean number of calls that had to be made to conduct a counseling call in prehypertensive subjects was 3.29 ± 1.55 (3.15 ± 1.54 in Argentina, 2.58 ± 0.96 in Guatemala and 4.12 ± 1.65 in Peru). The overall median number of counseling calls was six (IQR 4–8) with no differences observed across the countries. With regard to SMS, 58.3 % of the participants reported that they received the SMS. Attrition rate was 13 % (24 % in Argentina, 10.5 % in

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S. Hostettler et al. (eds.), *Technologies for Development*,
DOI 10.1007/978-3-319-16247-8_12

Guatemala, and 4.7 % in Peru). The delivery of the intervention was challenging in the three countries with differences among them in process results. Process evaluation methods and metrics are useful to assess whether the intervention program was delivered as planned.

12.1 Introduction

In Latin America, hypertension and prehypertension are reaching epidemic proportions and represent a significant public health problem (Yusuf et al. 2001; Hernández-Hernández et al. 2010). Moreover, healthcare systems are facing challenges in terms of an aging population, increased prevalence of non-communicable diseases (NCDs), and rising healthcare costs. Although lifestyle interventions can reduce blood pressure in prehypertension and prevent progression to hypertension, current primary care systems in the region lack of effective health promotion programs.

Mobile health strategies have been shown to improve patient provider communication, encourage behavior change, and assist in chronic disease management (Fjeldsoe et al. 2009; Cole-Lewis and Kershaw 2012). Additionally, it has been shown that positive results occur in chronic disease outcomes in low- and middle-income countries (LMICs) where NCDs constitute a major component of the disease burden (Beratarrechea et al. 2014; Krishna et al. 2009; Glassman et al. 2010). In fact, although more evidence is still needed in LMICs, mHealth is considered an increasingly attractive intervention to improve health care delivery and access. However, mHealth needs to be integrated into primary healthcare systems and tailored to be more affordable, effective, and accessible, especially for disadvantaged groups in LMICs (Mechael et al. 2010). On the other hand, there is a growing need for high quality mobile health research, especially in developed countries for mHealth to be effective and sustainable. Randomized controlled trials (RCTs) are the gold standard for evaluating interventions in health services research, but they require standardized interventions to be implemented uniformly to a target population (Glasziou et al. 2010, 2012). However, these conditions are difficult to be met in health promotion interventions where social and environmental factors vary considerably. For this reason, recommendations have focused on the need to gather contextual and process data in RCTs. Process evaluation is essential in the development, piloting, and evaluation of new interventions (Irvine et al. 2012; Evans et al. 2012; Whittaker et al. 2012). It assesses the extent to which an intervention is delivered as planned during design.

The present study describes the processes related to the implementation of mHealth interventions for lifestyle modification in a pragmatic RCT conducted in prehypertensive subjects in Argentina, Guatemala, and Peru in low-resource urban settings.

12.2 Methods

12.2.1 Background of the Study

The main objective was to evaluate the effectiveness of an mHealth intervention focused on behavior change, which included short message services (SMS) and one-to-one telephone calls to promote lifestyle modification and reduce blood pressure in persons living in poor urban settings in Argentina, Guatemala, and Peru. The study was designed as a proof-of-concept intervention in three Latin American countries that encompassed a wide range of environments and health care settings. The study included three phases: a formative phase, focusing on the development and validation of culturally appropriate messages and algorithms for lifestyle modification; a pilot study; and an intervention phase consisting of a one-year RCT to compare intensive education for lifestyle modification to standard care. During one year, each subject of the intervention group received a monthly call to her/his mobile phone from a trained caller to receive counseling and advice on the adoption of healthy behaviors (counseling call). Additionally, a series of validated SMS tailored to the individual state of change were sent weekly to promote physical activity, increase intake of fruits and vegetables, and to reduce fat and sugar consumption. SMS were based on the Transtheoretical Model (Di Noia and Prochaska 2009). A total of 212 subjects (30–60 years old) per country were recruited in primary health clinics and community settings and assigned to an intervention or a control group. Blood pressure, anthropometric measurements, and behavioral risk factors (physical activity, diet, stress, and alcohol and tobacco use) were assessed at baseline and at months 6 and 12 of follow-up.

As part of the process evaluation, we assessed reach (proportion of the intended target population who received the intervention), fidelity (degree to which the intervention was conducted as planned), dose (components implemented), and attrition (percentage who actively dropped out of the intervention). We also analyzed factors related to basal characteristics, patterns of cell phone use, and process measures associated with attrition through a multivariate analysis. A web-based platform designed to support the intervention and collect data of the motivational counseling calls and SMS was used to evaluate how the intervention was being implemented.

12.3 Results

12.3.1 Enrollment

2630 subjects were screened in primary care centers and community settings located in low resource settings. 832 were eligible to participate in the study and 637 (76.5 %) of the target population were accepted to participate and included in the study, 212 in Argentina, 213 in Guatemala, and 212 in Peru.

Table 12.1 Baseline characteristics of participants by study arm

Characteristics	Total $n = 637$	Intervention group $n = 316$	Control group $n = 321$
Women (%)	53.7	49.4	50.5
Age (years), mean (DS)	43.4 (8.4)	43.6 (8.4)	43.2 (8.4)
Less than 7 years of education (%)	17.7	17.1	18.4
7–12 years of education (%)	37.2	37.6	32.7
More than 12 years of education (%)	47.1	45.2	48.9
Employment (%)	71.1	70.6	71.6
Household income, first quintile (%)	9.5	9.2	9.8
Without health insurance coverage (%)	38.5	41.7	35.2
Systolic blood pressure mmHg, mean (SD)	127.6 (6.3)	127.7 (6.3)	127.6 (6.4)
Diastolic blood pressure mmHg, mean (SD)	77.5 (6.4)	77.5 (6.5)	77.6 (6.4)
BMI, (kg/m^2) mean (SD)	30.5 (5.2)	30.2 (5.2)	30.8 (5.3)

12.3.2 Baseline Results

Table 12.1 outlines the baseline characteristics. There were no significant differences between the arms of the study. However, differences were observed between countries in terms of: household income, health coverage, and educational attainment. Seventeen percent of the participants included were in the first and second quintile of household income in Guatemala, 31.2 % in Peru, and 33 % in Argentina ($p < 0.001$). With regard to health coverage, 52 % of the participants in Guatemala had no coverage, 38.7 % in Peru, and 24.5 % in Argentina, ($p < 0.001$). Moreover, the level of educational attainment was: 37 % in Guatemala, 9.5 % in Peru, and 6.6 % in Argentina for less than 7 years of education; 14.2 % in Guatemala, 51.8 % in Peru, and 39.6 % in Argentina for 7 to 12 years of education; and 48.8 % in Guatemala, 38.7 % in Peru, and 53.8 % in Argentina for more than 12 years of education ($p < 0.001$).

12.3.3 Usage of Cell Phones

Most of the participants in the three countries indicated they had personal cell phones for personal use but patterns of usage differed across the countries (Table 12.2). We observed a significant trend between quintiles of income and expenditure on mobile phone services in the three countries. Sixty-three percent of the participants in the first quintile of household income group expended less than

Table 12.2 Patterns of cell phone use among the study participants in Argentina, Guatemala, and Peru

Patterns of cell phone use	Argentina $n = 212$	Guatemala $n = 213$	Peru $n = 212$	p value
Voice related use (%)	90.5	100	100	0.001
Non voice related use (text messaging) (%)	86.3	59.6	53.7	<0.001
Non voice related use (internet) (%)	12.3	26.7	5.2	<0.001
Prepaid service plan (%)	38.2	74.6	82.1	<0.001
Expenditure on mobile phone services (US$/month)				
Between US$4–7/month (%)	18	45.1	35.5	<0.001
Between US$8–11/month (%)	46.4	21.6	28.4	
Between US$12–15/month (%)	23.2	8.4	18.5	
More than US$15/month (%)	12.3	24.8	17.5	
Frequency of making phone calls				
Never (%)	7.1	0	0	<0.001
Less than one call a day (%)	20.3	5.2	7.5	
One call a day (%)	13.7	8.4	12.7	
Two or three times a day (%)	31.1	35.7	37.7	
Four or more times a day (%)	27.8	50.7	41.5	

US$7 per month on mobile services compared to 12.2 % in the fifth quintile. On the contrary, only 3.3 % of the participants expended more than US$15 per month in the first quintile group compared to 45.6 % in the fifth quintile group.

12.3.4 Process Results of the mHealth Intervention

316 participants were randomized to the intervention arm. We reached 98.7 % of the intervention population. Only four participants were never contacted by the caller after randomization, 18 (5.6 %) received only the introductory call, 188 (68.6 %) received at least half of the calls, and 111 (40.5 %) received more than 75 % of the scheduled calls.

During the study, the mean number of calls that needed to be made to contact a prehypertensive subject to conduct a counseling call was 3.29 ± 1.55. Differences were observed between the three countries: a mean of 3.15 ± 1.54 calls was needed to contact a participant in Argentina, 2.63 ± 0.93 calls in Guatemala, and 4.12 ± 1.65 calls in Peru ($p < 0.001$).

12.3.5 Intervention Fidelity and Dose Received

The intervention package included an introductory call, 12 mobile phone counseling calls, and 48 SMS messages during the year of intervention. However, the overall median number of counseling calls was 6 (IQR 4–8). No difference in the median number of counseling calls was observed across countries (p = NS). The median duration of the counseling calls was 21 min (IQR 16–26) in all the countries: 17 min (IQR 14–27) in Guatemala, 22 min (IQR 18–25) in Peru, and 21 min (IQR 17–25) in Argentina ($p = 0.01$). In addition, less SMS were delivered than planned. The median number of SMS sent was 23 (IQR 13–32). Differences were observed across the countries, with 21 SMS (IQR 10–28) sent in Guatemala, 25 (IQR 15–34) SMS in Peru and 24 SMS (IQR 10–34) in Argentina, ($p = 0.018$). Since the computer program used to deliver SMS could not record whether messages delivered were opened, we asked participants in every call whether they read SMS and how many they received. In this sense, 58.3 % of the messages sent were received overall. In Guatemala, participants reported receiving 82 % of the SMS sent, while in Argentina and Peru fewer messages were received, 50 and 46.2 %, respectively.

To define dose, we used the definition proposed by Voils et al., which defines it as the "exact amount of a medicine or extent of some other treatment to be given or taken at one time or at stated intervals" (Voils et al. 2012). To operationalize this variable, we added the total duration in minutes of all the mobile counseling calls delivered to each participant. The overall median dose was 122 min (IQR 66–175). Participants in Peru were exposed to higher doses, a median of 144 min (IQR 98–201), compared to participants in Argentina and Guatemala, with 115 min (IQR 55–184) and 99 min (IQR 57–149), respectively ($p < 0.001$). The overall attrition rate was 13 %. It differed between the countries and it was higher in Argentina (24 %) compared to Guatemala (10.5 %) and Peru (4.7 %, $p < 0.001$).

We conducted a multivariate analysis to determine which factors were associated with attrition. In fact, we found that independent predictors in our study were: the number of calls to contact a participant (OR 0.20 per each additional call, $p < 0.001$), the number of counseling calls completed (OR 0.41 per each additional counseling call completed, $p < 0.001$), being an Argentinean participant (OR 8, $p = 0.004$), and a monthly expenditure of mobile services of more than US$15 (OR 0.09 compared to the spending of less than US$7, $p = 0.047$).

12.4 Discussion

In the mHealth field, little is known about how to do mHealth well, especially in LMICs, where resources are scarce. It is essential to evaluate those factors influencing how and why mHealth interventions work. In developed countries, evidence about the likely uptake, best strategies for engagement, efficacy, or effectiveness should guide the adoption of new technologies (Tomlinson et al. 2013).

Process evaluations within trials help in the interpretation of the outcome results as they explore the implementation, receipt, and setting of an intervention (Oakley et al. 2006). Few papers have reported the processes related to the implementation of mHealth interventions (Evans et al. 2012; Whittaker et al. 2012). In addition, a recent systematic review that examined how mHealth was used to strengthen health care systems to address the growing NCD burden in LMICs showed that none of the studies included reported any qualitative or process evaluation of the interventions (Peiris et al. 2014).

In this paper, we described the process of the implementation of an mHealth intervention that included cell phone voice and short text messages in low resource settings in three LMICs to promote behavior change. In particular, this study provided a method for assessing the extent of participants' engagement with mHealth and the likely uptake of this intervention in the target population.

Although prehypertensives were recruited from low resource settings, we found differences regarding sociodemographic characteristics in the included subjects across the countries. In Guatemala, participants were less educated, the proportion of participants without health coverage exceeded 50 %, but had higher income compared with participants in Peru and Argentina. On the contrary, participants in Argentina were more educated, more than half of the population had health coverage, but one in three participants had low household income. These variations showed a different social context.

We also found differences in the patterns of cell phone use among the countries that might have influenced process results. In Peru, participants reported receiving only 46.2 % of the SMS sent, which might be related to the low use of text messaging reported at baseline. Conversely, the frequency of making calls in Argentina was lower compared to Peru and Guatemala, but it did not have an impact on the mean number of counseling calls.

The delivery of the intervention was challenging in the three countries. Although we reached a high proportion of the target population, the intervention was not delivered as programmed. We experienced difficulties in contacting participants and the dose was lower than outlined in the project protocol. During the pilot study, we included 46 participants to test the feasibility of the intervention. In this phase, we found that the mean number of calls to contact a participant to conduct a counseling call was lower (2.3 ± 1). In fact, we expected this indicator to improve during the intervention phase. Attrition rate was high in Argentina, and this was an independent risk factor for dropping out of the intervention. We analyzed variables related to sociodemographic characteristics, patterns of cell phone use, and process measures to determine association with attrition. We found that spending more than US$15 per month in mobile services, a high number of attempted contacts to complete a call, and the number of counseling calls completed were associated with lower risk of dropout.

A limitation of this study was that it did not include qualitative information to understand the barriers related to implementation and the reasons for attrition. Socioeconomic aspects and user acceptance are factors that might drive a successful mHealth intervention. Low cost of mobile services promotes usage and can have an impact on the willingness to participate in mobile health programs (Norris et al. 2009). Indeed, we found that those who spend more money on mobile services adhered more to the proposed mHealth intervention. Indeed, mHealth must be affordable, reliable, easy to use, convenient, and must also fit with existing lifestyles to be widely adopted (Norris et al. 2009; Ganapathy and Ravindra 2009; Ginige et al. 2014).

Decisions regarding dose and delivery must be made when translating effective interventions into clinical practice because the complexity and resource intensity of interventions require modifications to be feasible in different settings and contexts. Process evaluation methods and metrics are useful for assessing whether the intervention program was delivered as planned and for scaling-up novel interventions like mHealth in developed countries.

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Chapter 13
Designing Suitable Assistive Technology for the Population with Motor Disabilities in Colombia

Ricardo Chavarriaga, Manuel Valencia, Maria Hurtado, Marcela Bolaños and Jaime Aguilar-Zambrano

Abstract Assistive technology promotes a greater level of autonomy and favors social inclusion in people with motor disabilities. Product design of assistive technology should take into account the sociocultural aspects of potential users to provide effective solutions according to context requirements. The authors established a research line on the development of technology-based assistive solutions using an Expanded Model of Axiomatic Design. It is based on an interdisciplinary approach that puts the user at the center of the design process so as to effectively identify the needs of the users in context of Colombia, where violence is the main cause of motor disability. The authors designed a wheelchair for mobility and a rehabilitation station facility for supporting neural therapy. This research was the result of collaboration between Swiss and Colombian institutions, allowing the authors to develop and apply state-of-the-art technology tailored to the specific needs of the community. It also allowed the authors to strengthen the research capabilities of local institutions and establish a valuable test bed for transnational research in this field.

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S. Hostettler et al. (eds.), *Technologies for Development*,
DOI 10.1007/978-3-319-16247-8_13

13.1 Introduction and Purpose

Disability is a worldwide problem and, currently, it is analyzed under an ecological and psychosocial approach that is different from an exclusively biomedical approach. The context and causes of this problem are different in developing countries than in developed countries. For example, the authors have found that people with motor disabilities in Cali, Colombia are in this situation mainly due to violence (Hurtado et al. 2012). However, in Europe, the first cause is accidents while violence is one of the last (Hurtado et al. 2012). Another aspect associated with disability in developing countries is the lack of appropriate public infrastructure, and that people without physical limitations are not prepared to interact effectively with people who have disabilities (Hurtado et al. 2012). These elements contribute to a social exclusion of the population with motor disabilities. Therefore, it is necessary to approach the analysis of this problem and the design of a new product from different disciplines, due to its complexity. Furthermore, integration of new scientific knowledge in the design process may lead to innovative products that favor the social inclusion of people with disabilities.

In this paper, the authors show the process and results in product design using the Expanded Model of Axiomatic Design (Aguilar-Zambrano et al. 2012) applied to assistive technologies. This product is the result of collaboration between Colombian institutions (Pontificia Universidad Javeriana, Universidad del Valle, Centro de Neurorehabilitación SURGIR) and a Swiss research partner, the Defitech Chair in Non-Invasive Brain-Machine Interface (CNBI) at the Ecole Polytechnique Fédérale de Lausanne (EPFL).

13.2 The Expanded Model of Axiomatic Design for Assistive Products for People with Disability

The Expanded Model of Axiomatic Design is a model based on axiomatic design to control the design process. It includes a multidisciplinary team of design focused on the user's needs and works with perceptual requirements (Aguilar-Zambrano et al. 2012). The model strengthens the analytical and creative phases of the design process using techniques of the Theory of Inventive Solving Problem—TRIZ (Salamatov 1999). In this way, products are considered as technical systems that have a main function (Savransky 2000). The Expanded Model of Axiomatic Design defines three steps in the design process, as shown in Fig. 13.1a. The model uses a Technical System to describe a product that carries out a main function with the following parts: motor, transmission, tool, and control. The technical system requires energy for functioning and an object to apply the main function. The use of the Expanded Model of Axiomatic Design for assistive products adapts the technical system, since the person himself is the technical system that has a malfunction due to a physical limitation that needs to be restored (Aguilar-Zambrano et al. 2012).

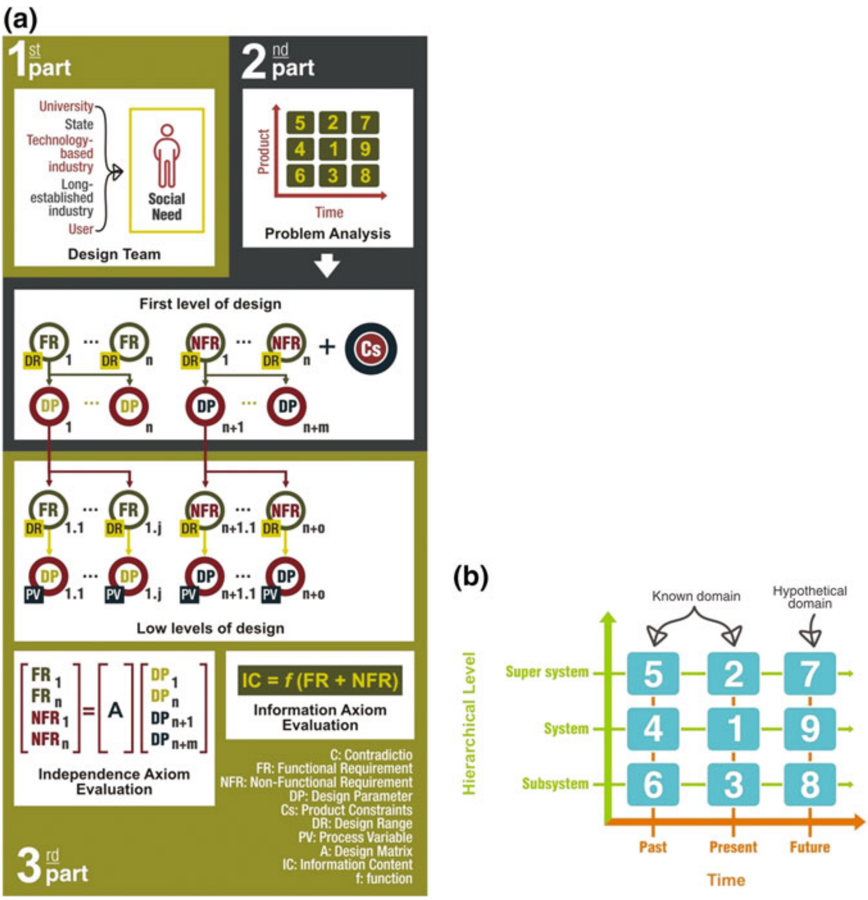

Fig. 13.1 **a** Model of expanded model of axiomatic design. **b** Nine windows technique

13.2.1 Method of Expanded Model of Axiomatic Design

The method of the Expanded Model of Axiomatic Design has three parts: The first part consists of formulating the problem, conforming the design team, and identifying the user. The second part consists of defining the main function of the product and its associated technical system, requirement definition, and a proposal for the first conceptual design. The third part consists of the final design using Axiomatic Design to control the design process with observance of two axioms: Independence and Information.

In the first part, the interdisciplinary team must include engineers and industrial designers together with professionals associated with the problem, for example physicians in the case of health problems. In the second part, a systemic analysis of the problem is performed using the nine windows technique of TRIZ. This technique gives a view of the problem in the past, present, and future in the different levels of the system. As shown in Fig. 13.1b, it starts with the system at the present time and ends in the future of the system (Savransky 2000). A comparison between the future and the present characteristics of the technical system generates a set of conflicts due to the impossibility of the current system to achieve the expected attributes of the future system. Those conflicts yield the product requirements. The design team propose a first set of alternatives of conceptual design that responds to requirements established using the contradiction matrix of TRIZ for that purpose (Gonzalez et al. 2008). In the third part, the Axiomatic Design allows structuring the design process following two axioms. The Functional Requirements of the product (FRs) are defined with a Design Range (DR) and the Design Parameters (DPs) are proposed with a System Range (SR) using physical units. An optimal design is one that satisfies the FRs in all DR. This can be formalized in a probabilistic way (Eq. 13.1). Where m is the number of requirements and P_i is the probability to satisfy the requirement i. An optimal design satisfies all requirements (i.e., information content, I_{sys}, equal to zero),

$$I_{\text{sys}} = \sum_{i=1}^{m} \log_2 P_i. \tag{13.1}$$

13.3 Results

13.3.1 Assistive Product for Mobility

First part. *Main function*: To move a person who has a motor disability. *Technical system*: Person with a mobility limitation due to vertebral-medullar trauma. *User*: People with a motor disability belonging to formal associations of this population in Cali, Colombia. *Parts of the technical system*: Tool: Feet; Control: Brain and neural system; Transmission: Skeletal system; Motor: Muscle system of lower limbs. *Team composition*: Two electrical, two mechanical and one electronic engineer, two industrial designers, a psychologist, and an occupational therapist.

Second part. From the systemic analysis using the nine windows technique, the authors highlight in this paper only two windows from which they derived the requirements of the product: technical system in present time and technical system in future. **Technical system in present time**. The current systems for improving the mobility are technical systems that operate as prosthesis classified in the ISO9999 standard (UNE 2007). The analysis of these types of products worldwide showed that these products have ergonomic considerations in the design and there are different types of products for different activities. The authors conducted a survey among people with motor disabilities in Cali with the purpose of identifying their needs and barriers of social inclusion. The authors found that the main known product used and needed was the manual wheelchair (98 %), the products are purchased with own economic resources (41 %) and with state contribution (15 %). The most common wheelchair used is the push rim. This device has a negative effect in the upper articulations caused by excessive effort with the arms. On the other hand, the users want the product to take care of their health, be adjustable according to the limitation, safe, easy to drive, portable, and to help them change positions between sitting and semi-standing. **Technical system in future**. The ideal system should be the person without limitation who can move without prosthesis. The physical characteristics of people with disabilities are: to walk in different terrains, maintain a velocity of 5 km/h, and reach objects above their head in a semi-standing position. Additionally, the person must have movement control that includes walking, stopping, and turning. **Requirements**: The authors found four requirements for the system, continuing with the prosthesis line and the local limitation to restore the neural connection as the contradiction analysis suggested: Displace the technical system (DR: 0.55–1.46 m/s), carry the user (DR: 75–100 kg), commute between sitting and semi-standing positions (DR: 0°–80°), and reconfigure the system to facilitate its folding and transport (DR: 30–50 % of total volume).

Third part. **Use of Axiomatic Design for one proposal selected**. The authors selected four conceptual design proposals and one alternative for a detailed design. The system was designed to satisfy the two axioms, as shown in Fig. 13.2.

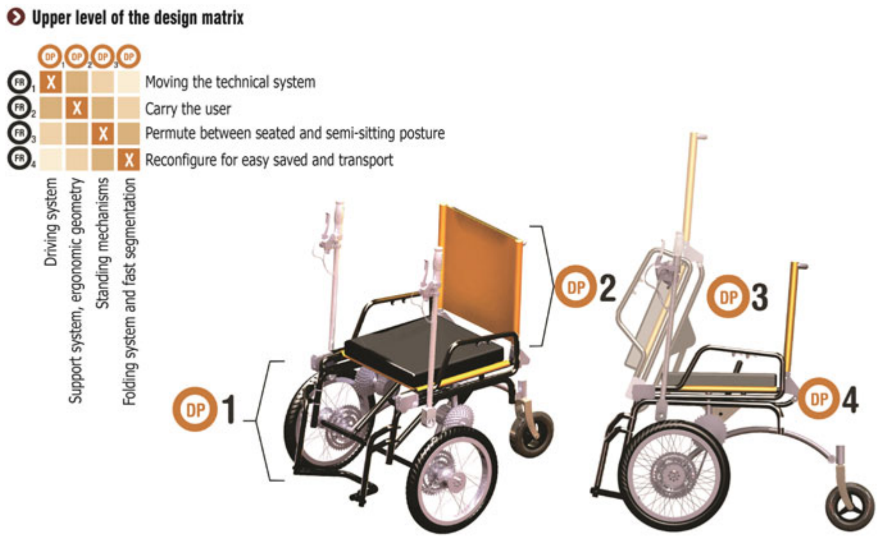

Fig. 13.2 System designed with the use of expanded model of axiomatic design

13.3.2 Facility for Rehabilitation Therapy

First part. *Main function*: Improve rehabilitation therapy. *Technical system*: Person with reduced mobility in one upper limb due to a stroke. *Parts of technical system*: Tool: Hand; Control: Brain and neural system; Transmission: Skeletal system; Motor: Muscle system of upper limb. *User*: People in Cali, Colombia, with hemiplegia due to a stroke. *Team composition*: Two electrical and two electronic engineers, one industrial designer, one physiotherapist, and one occupational therapist.

Second part. **Technical system in present time**. The current therapy, used in the associated center of the project, is Bobath reeducation within the Ecological Theory in motor control. Cushions, mirrors, chairs, accessories, and beds are used in the therapy as a station without tracking and measuring the patient's movement during the therapy. Virtual feedback is used in experimental studies in some medical centers to improve the therapy (Broeren et al. 2008; Makowski et al. 2013). **Technical system in the future**. The system must have the ability to record and measure the activity during the therapy. The patient must have more interaction during the therapy process and reduce the time with the physiotherapist. The activities in the sitting position during the therapy must allow for reaching, catching, grasping, pushing, and pulling objects. **Requirements**: The authors proposed a set of main requirements to improve the rehabilitation therapy in consonance with the ecological therapy and conflicts identified with the nine windows technique. The requirements were: (1) Align the body in decubitus position (70–100 kg); (2) Align the body in a sitting position (70–100 kg); (3) Move upper limbs in functional activities (70–100 kg); (4) Locate objects in the spatial position (90°–180° in sagittal plane, and 30°–150° in transversal plane and 90–180 in frontal plane); (5) Measure trajectory of movement of an upper limb (90°–180° in sagittal plane, and 30°–150° in transversal plane and 90–180 in frontal plane); (6) Record the time of the movements of therapy (Spatial coordinates 0–180 in sagittal, transverse and frontal plane); (7) Give visual feedback of activity (Image in sagittal, frontal and transverse planes); (8) Store personal information and therapy type (Data file); (9) Allocate devices for neuromuscular stimulation therapy (area 0.50 × 0.50 m).

Third part. **Use of Axiomatic Design for one proposal selected**. The system designed, shown in Fig. 13.3, has two complementary parts: one is associated with the furniture or hardware for the therapy and the second is the instrumentation and software support for the station with the purpose to measure, stimulate, and record the activity during the therapy. The system contains: bed, chair, screen, and motion tracking system with a central computer with software support. The software platform allows the physiotherapist to record personal patient information, evaluate the therapy and access records of the historical performance of the patient.

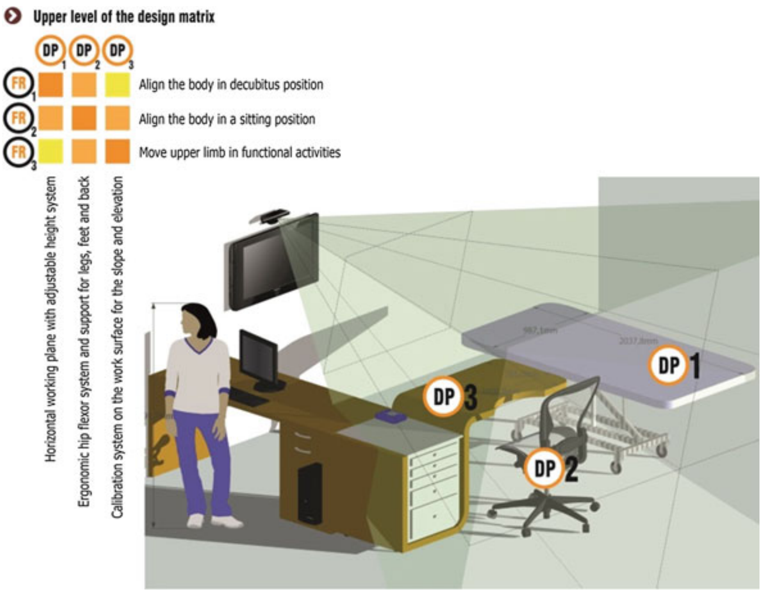

Fig. 13.3 Conceptual design of a rehabilitation station facility

13.4 Learning and Dissemination of Results

The results obtained in the design process and the survey results have been disseminated to different institutions, including the Disability Committee of the Municipality of Cali. The authors have offered two interdisciplinary courses for creativity and about product design for rehabilitation using new advances in neuroprosthetics. The authors have also written papers targeting different disciplines: Design (Aguilar-Zambrano et al. 2013b), Engineering, (Aguilar-Zambrano et al. 2012, 2013a) and Health (Hurtado et al. 2012). The design team in Cali, Colombia received training on different uses of experimental systems for improving the rehabilitation therapy developed by EPFL-CNBI (Chavarriaga et al. 2014).

13.5 Conclusion

Interdisciplinary work is an adequate strategy for facing complex design problems because it considers the problem from different points of view, which strengthens the analysis. In this study, the participation of physiotherapists and an occupational therapist allowed the authors to understand the social inclusion concept and the rights of people with disabilities. The Expanded Model of Axiomatic Design is a framework to control the design process and allows a dialogue with different disciplines involved in the design process.

Collaborative work between partners allows for the appropriation and use of new technologies and advancements in the research in product design and neuroprosthetics. These projects were useful to promote the participation of undergraduate and graduate students of different disciplines regarding a social problem, allowing them to share knowledge and develop new competencies in their professional work. The collaboration with EPFL-CNBI was necessary in the design process because in Colombia, there is no strong research on neural control, and it was detected as a necessity in the first design for reaching the ideal technical system corresponding to a person without limitation.

Acknowledgments This work has been supported by Colciencias and the Cooperation and Development Center (CODEV) at the Ecole Polytechnique Fédérale de Lausanne (EPFL). The authors would like to thank all the people who took part in the activities described here.

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Chapter 14
ReMotion Knee: Scaling of an Affordable Prosthetic Knee for Developing Countries

Samuel Hamner, Vinesh Narayan, Nicole Rappin and Krista Donaldson

Abstract Amputees living in developing countries have a profound need for affordable and reliable lower limb prosthetic devices. The World Health Organization (WHO) estimates that there are approximately 30 million amputees living in low-income countries, 85–95 % of whom lack access to prosthetic devices. Effective prosthetics can significantly change the lives of these amputees by increasing the opportunity for employment and providing improvements to long-term health and well-being. However, current solutions are inadequate: state-of-the-art devices are cost-prohibitive, while low-cost devices are often of poor quality and/or provide unreliable performance. The introduction of new devices is hampered by the lack of a cohesive prosthetics industry in low-income areas; the current network of low-cost prosthetic clinics is informal and loosely organized with significant disparities in geography, patient volume and demographics, device procurement, clinical and logistical infrastructure, and funding. D-Rev has designed the ReMotion Knee, an affordable polycentric prosthetic knee joint that performs on par with devices in high-income countries. As of October 2014, over 6200 amputees have been fitted with the JaipurKnee, the initial version of the ReMotion Knee, through a partnership with the Jaipur Foot Organization. D-Rev is currently scaling production of the ReMotion Knee using centralized manufacturing and distribution to serve existing clinics and increase the availability of devices for amputees without access to appropriate care. D-Rev aims to develop products that target these customers through economically sustainable models and provide measurable impact in the lives of the world's amputees.

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S. Hostettler et al. (eds.), *Technologies for Development*,
DOI 10.1007/978-3-319-16247-8_14

14.1 Introduction

The World Health Organization (WHO) estimated that there were 30 million amputees living in low-income countries in 2010 (Pearlman et al. 2008), yet only 5–15 % of those amputees will ever be fit with a prosthetic device (Andrysek 2010; WHO 2011) (Fig. 14.1). Even when amputees have access to a prosthetic clinic, up to 80 % of amputees are unable to afford a device (Cummings 1996). These statistics indicate that developing countries have a profound need for radically affordable lower limb prosthetics (Fig. 14.2). Existing solutions are inadequate. At one end of the cost spectrum, there are low-cost, locally manufactured knees that utilize a single-axis design. Single-axis knees rotate about a fixed axle—similar to the motion of a door hinge—which provides less stability and toe clearance during walking than polycentric knees (Radcliffe 1977; Gard 1996). In contrast, polycentric knees use linkages to move the axis of rotation as the knee bends, allowing the knee to slide and rotate more like the motion of a natural knee. At the other end of the cost spectrum, more expensive donated knees are inconsistent in supply, costly to maintain, and perform poorly in more rugged environments found in resource-limited settings. D-Rev aims

Fig. 14.1 Many amputees in developing countries rely on improvised or homemade solutions to move around. However, these solutions typically lead to less mobility than amputees could achieve with higher quality prosthetic devices. WHO estimates that 85–95 % of amputees in developing countries do not receive a prosthetic device (Pearlman et al. 2008; Andrysek 2010). These three patients from the Jaipur Foot Organization (BMVSS) in India show typical homemade solutions for amputees, including a bamboo staff and wooden crutch

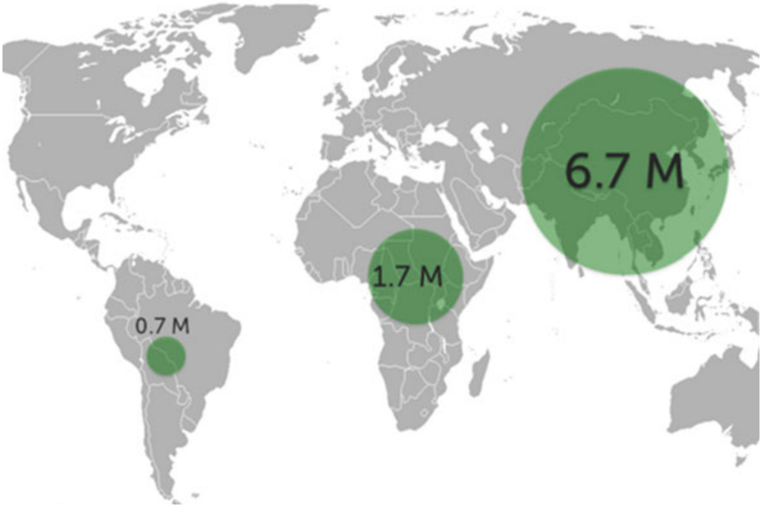

Fig. 14.2 Estimated total unmet need for prosthetic knee joints, based on estimated rates of above-knee amputees and country populations. D-Rev estimates that there are 6.7 million above-knee amputees in Asia (mainly China and India) in need of a prosthetic knee, 1.7 million above-knee amputees in Africa, and 0.7 million in South America (Andrysek 2010; UNFPA 2011; WHO 2011)

to address this gap in the market by developing the ReMotion Knee, an affordable polycentric prosthetic knee, which performs on par with more expensive polycentric knees, at a projected retail cost of US$80. Since 2008, over 6200 amputees have been fitted with the JaipurKnee in 14 countries, including India, Indonesia, Iraq, Sri Lanka, Senegal, and Fiji through D-Rev's partnership with the Jaipur Foot Organization, also known as Bhagwan Mahaveer Viklang Sahayata Samiti (BMVSS).

The JaipurKnee started as a student project at Stanford University in 2008. The Jaipur Foot Organization (BMVSS), one of the world's largest producers and fitters of low-cost prosthetics, worked with the student team to design a higher performing knee joint than its existing single-axis knee while meeting strict cost constraints. After the students developed prototypes at Stanford, BMVSS began fitting the JaipurKnee and reported improved gait quality and patient satisfaction (Fig. 14.3). Since 2009, the JaipurKnee has been locally manufactured in India by BMVSS. A team of students who had been involved with the JaipurKnee's design spun out of Stanford to design and develop a high quality, mass-produced knee that could reach amputees globally. In 2011, the student group was acquired by D-Rev to globally scale production and distribution of the ReMotion Knee. Table 14.1 summarizes development and key features of the JaipurKnee and the evolution of the ReMotion Knee.

Access to appropriate prosthetic devices significantly impacts the lives of patients, mainly through increased likelihood of employment. A prosthetic device provides the ability to stand, walk significant distances to work, or perform physical labor. Agriculture and other manual occupations provide the livelihood of up to 75 % of Indians (International Institute for Population Sciences 2007), and for

Fig. 14.3 The knee above is being worn by Kamal, the first patient fitted with the JaipurKnee—the predicate design for the ReMotion Knee—as he walks through the BMVSS clinic in Jaipur, India. Video of Kamal walking with the JaipurKnee can be viewed at http://d-rev.org/kamalwalking. This knee was designed for CNC machining to integrate with existing Jaipur Foot attachments. BMVSS began production in 2008 and has since fit over 6200 amputees in 14 countries including India, Indonesia, Iraq, Sri Lanka, Senegal, and Fiji

many, this is the only option to earn a living. Working in the fields or a factory is physically demanding, requiring uninterrupted hours of walking and standing—tasks that are difficult for lower limb amputees who lack appropriate mobility aids.

Effective prosthetic devices significantly increase an amputee's mobility and independence, which can increase confidence, well-being, and long-term health. Walking and increased mobility can develop and improve physical fitness, enhance metabolism, increase bone strength, improve cardiac performance, and reduce anxiety, stress, and depression. Furthermore, walking has the potential to reduce disability and handicap (Morris and Hardman 1997). Without appropriate aids, amputees' mobility is limited, which can lead to further inactivity and worsening disability. Additionally, in many cultures, amputees endure severe social stigma (Rybarczyk et al. 1995; Yinusa and Ugbeye 2003; Horgan and MacLachlan 2004).

The majority of existing prosthetic components target patients and environments in affluent economies. These components are not appropriate for large-scale impact in resource-limited settings; they are cost-prohibitive, require frequent maintenance, and are not designed for exposure to weather and varied terrain (Pearlman et al. 2008). Clinics in the nonprofit sector that purchase new knees often depend on small volumes of the cheapest option: knees made from stainless steel or titanium

Table 14.1 Summary of the development and key features of the JaipurKnee and the ReMotion Knee

JaipurKnee		
	*Description* The original JaipurKnee developed at Stanford in 2008 with the Jaipur Foot Organization. Over 6200 amputees fitted with 79 % compliance after 6 months	*Key features* • Original polycentric design • Used with Jaipur Foot threaded attachments • Designed for CNC Machining (either through local manufacturing or central production)
ReMotion Knee (prototype)		
	*Description* Refined design of a polycentric knee to incorporate features most requested by prosthetists and amputees. Manufactured in California and deployed to Ecuador for initial fittings in 2011	*Key features* • Curvature mimicking • Anatomical knee cap • Extension assist spring • Noise dampening bumper • Easier adjustment for fitting: standardized pyramid attachment
ReMotion Knee		
	*Description* Modified design for high-volume production with injection molding. Deployed in field trials to India, Indonesia, and Guatemala	*Key features* • Designed for injection molding (mass, centralized manufacturing) • Reduced weight and size compared to previous versions • Modern design esthetic that better mimics an anatomical knee cap

and designed with single-axis mechanisms. Even with the lowest cost option, organizations find that they are unable to finance sufficient quantities of components to meet the need at their clinics (Pearlman et al. 2008).

In this paper, we present an overview of the existing prosthetics market in low-income countries, including current market limitations, our approach to design and distribute effective products, an overview of user testing, and technical specifications and user requirements for the ReMotion Knee. We are calling on the international development community to increase care provided to amputees and people with disabilities living in underserved regions toward a level of care seen in high-income countries. We also discuss strategies to scale production and distribution to sustainably reach amputees in low-income countries who currently do not have access to effective prosthetic devices. Finally, we put out a call for large-scale impact assessment of interventions, like the ReMotion Knee, to ensure patients are provided effective medical care.

14.2 Design and Methods

14.2.1 Design Process

D-Rev's mission is to improve the health and/or increase the incomes of people who live on less than US$4 per day through the design and delivery of affordable, world-class products. D-Rev's current product line includes the ReMotion Knee and Brilliance, a phototherapy device to treat severe neonatal jaundice, which is currently on the market. Our process has five main stages: Identify, Design, Deliver, Scale, and Measure (Fig. 14.4).

- *Identify* high impact opportunities that can close the quality healthcare gap for under-served populations.
- *Design* products to meet customer needs and incorporate needs of manufacturing, distribution, servicing, and other key stakeholders.
- *Deliver* product to users by integrating into the existing market.
- *Scale* appropriately for maximum global impact.
- *Measure* impact to determine that the product is reaching the people who need it and providing effective outcomes.

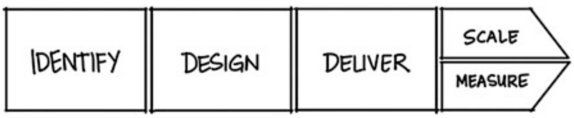

Fig. 14.4 D-Rev's process for development and delivery of affordable, world-class products that improve the health and income of people living on less than US$4 per day. Our process has four main stages: (1) Identify, (2) design, (3) deliver, (4) scale, and (5) measure

14.2.2 Market Landscape

The current landscape of low-cost prosthetists is comprised of loosely organized networks of clinics and independent operators that vary greatly by geography, the number of amputees fit annually, patient demographics, sources of components, and funding models. The market is fragmented, composed mostly of small clinics with insufficient capacity, and overburdened by a large patient population and underdeveloped distribution channels. We categorized market fragmentation and variability between clinics using three main criteria: (1) sourcing of prosthetic components, (2) financial structure, and (3) patient billing. For sourcing, we observe that clinics rely on donations of used devices, locally manufacture their own devices, and/or purchase components from a private sector distributor. For financial structure, clinics can be characterized as public (government) clinics, private for-profit clinics, nonprofit, nongovernmental organizations (NGOs), or mission-based. Finally, the financial relationships between clinic and patient include donated free services, partially subsidized care (by the government or philanthropic groups), and full payment by the patient.

We believe that broad social impact will be achieved when the capacity of the existing prosthetics market is not only met, but increased. Through fieldwork and landscape analysis, D-Rev has identified limiting factors for the prosthetics market that currently affect clinics and amputees in low-income regions.

14.2.2.1 Limiting Factors for Clinics (Market Supply)

- *Lack of trained technicians*. There is a severe shortage of trained prosthetists in low-income countries (WHO and IPSO 2004). Trained prosthetists are required for properly fitting amputees. Socket fit, prosthetic alignment, and gait assessment are critical for successful outcomes and full patient satisfaction.
- *Cost of devices*. Most prosthetic devices on the global market are designed and priced for high-income markets. Their retail prices are orders of magnitude higher than what low-income clinics can afford, and clinics are unable to pass these costs on to their patients.
- *Supply of devices*. We learned from clinic interviews that unreliable supply of quality prosthetic devices and components is a significant hindrance, slowing or stopping fitting. Reusable donated parts are of limited supply. More expensive commercially available knees can be difficult to obtain in low-income markets. In-house manufacturing requires management of supply chain, inventory, and quality control, which can overburden clinic resources and reduce time for patient work.
- *Device quality*. Prosthetists working in low-income regions have had significant problems consistently procuring high-quality components and materials. Donated components are typically used, resulting in reduced product lifetimes and poor performance along with servicing and maintenance challenges. Locally

manufactured components need a quality control process to ensure consistent quality, which is resource-intensive for self-manufacturing clinics.

- *Funding*. Clinics selling devices are often forced to subsidize costs and/or find sponsoring organizations to be economically viable. Clinics that provide free prosthetic systems and fitting must rely on government and/or grant funding.

14.2.2.2 Limiting Factors for Amputees (Market Demand)

- *Lack of clinic awareness*. Many amputees are simply unaware of affordable opportunities for remobilization—at local clinics, temporary fitting camps, and/or other outreach programs. Building awareness throughout communities will be critical for serving more patients.
- *High perceived cost*. Many of the amputees we interviewed assumed that the cost of a prosthetic leg system was unaffordable to them. However, in many parts of the world there are programs to provide prosthetic devices either at no cost or partially subsidized at an affordable cost.
- *Distance from clinic*. Lack of access to transportation prevents many amputees from reaching appropriate care facilities, or returning for follow-up maintenance or refitting.
- *Accommodations and fitting logistics*. Prosthetic fitting and gait training spans multiple days or even weeks, which can lead to logistical challenges and financial hardship for patients. Amputees in many clinics also bring family members, meaning an extended fitting process can cause a significant loss of family income.

14.2.3 User Testing

14.2.3.1 User Feedback from the JaipurKnee

With over 6200 patients already fit with the JaipurKnee, we have a large pool of users to help us identify key design features critical for adoption. For example, prior to user feedback we hypothesized that increased range of motion—which allows squatting and sitting cross-legged—would be a key feature to patients. While this feature was desired, we learned after interviewing hundreds of patients that minimizing any noise, improving cosmesis, and the ability to ride a bicycle were also of high priority. We also learned that the natural walking motion provided by the ReMotion Knee was critical for adoption because many patients desire to not be identified as an amputee, which can lead to social stigma (Rybarczyk et al. 1995; Yinusa and Ugbeye 2003; Horgan and MacLachlan 2004). Through our relationship with the Jaipur Foot Organization (BMVSS), we conducted a follow-up survey by phone with 141 patients in 2010. Survey results showed that 79 % of patients were still wearing their prosthetic device up to six months after fitting. While 95 % of patients reported no failures of the ReMotion Knee, 21 % asked to reduce the knee's clicking noise.

14.2.3.2 Field Trials with the ReMotion Knee (prototype)

As D-Rev works to bring the ReMotion Knee to market, we also conducted four-to-six month longitudinal field trials at four clinics in India, Indonesia, and Guatemala. Clinics were selected from 11 potential sites to represent the varying models we observed in our market landscape analysis. Additionally, all clinics had trained prosthetists to properly fit the knee and an existing system to conduct follow-up with patients—follow-up was one of the biggest challenges in conducting a longitudinal study. The trials had two main goals: (1) evaluate effectiveness and mechanical integrity of the knee, and (2) better understand how the knee affects patients' lives through impact data collection. To achieve these goals, we utilized a blend of objective measures of mobility, such as the 10-m walk test (Deathe and Miller 2005) and the timed up and go test (Schoppen et al. 1999), as well as more subjective surveys that assess satisfaction with the prosthetic device, fitting quality, quality of life, income generation, and psychosocial adjustment (Grisé et al. 1993; Legro et al. 1998; Condie et al. 2006; Gallagher et al. 2010). Finally, to ensure safety and protect patients' rights, the study protocol was also approved by Stanford's Institutional Review Board (IRB).

14.2.4 Technical Product Features

The key innovation of the ReMotion Knee (Fig. 14.5) lies in the use of a proven polycentric mechanism (Radcliffe 1977, 1994, 2003), typically made from steel or titanium, designed for strength, durability, and centralized manufacturing with low-cost polymers. Compared to existing low-cost prosthetic knee joints with a single-axis mechanism, such as the knee developed by the International Committee of the Red Cross (ICRC) (CR Equipments 2013), the polycentric ReMotion Knee provides increased stability and improved gait efficiency. The ReMotion Knee is also designed to include the most important technical features for prosthetic knees in developing countries, as determined at the State-of-the-Science Conference on Appropriate Technology for Rehabilitation in Developing Countries (Rehabilitation Engineering Research Center on Improved Technology Access for Landmine Survivors 2006).

Fig. 14.5 A ReMotion Knee prototype. These prototypes were assembled in California for field testing at clinics in India, Indonesia, and Guatemala. Added features included curvature mimicking anatomical knee cap, noise dampening, and standardized attachment systems (i.e., pyramid and 30 mm pylon). The latest version of the ReMotion Knee will be available for clinics to purchase in the second quarter of 2015

14.2.5 User Needs

In addition to technical and performance specifications of the prosthetic knee, D-Rev also aims to identify and meet the needs of users—patients and prosthetists. In particular, we focus on aspects of adoptability. For the patient, this includes providing a natural walking motion, ability for high range of motion, reducing or eliminating clicking or other noise while walking, and giving the knee a curved shape that looks like a natural knee when worn under clothing. These features aim to improve mobility for the patients, while minimizing the social stigma that many amputees endure (Rybarczyk et al. 1995; Yinusa and Ugbeye 2003; Horgan and MacLachlan 2004). For prosthetists, this focus on adoptability means designing the knee to interface with existing fitting systems, such as pyramid connectors and other standardized hardware, and allowing for critical adjustments of alignment and friction control.

14.2.6 Manufacturing and Distribution

Our strategy to manufacture and distribute the ReMotion Knee will leverage the private sector to effectively and affordably deliver the knee to our customers—clinics and their patients. To achieve this goal, we work with for-profit manufacturing and fulfillment partners. The fulfillment partner will warehouse, package, and ship the knee to clinics, as well as conduct quality inspections on random samplings of knee units received from the contract manufacturer. The contract manufacturer will be responsible for any units found to be outside of specifications, creating an incentive structure for the manufacturer to produce components that meet our technical specifications. Additionally, D-Rev will assess and implement regulatory compliance and local distributor strategies on a country-by-country basis to ensure lowest cost and ease of procurement for prosthetic clinics.

The goal of the ReMotion project, as with all D-Rev projects, is to serve customers in low-income countries through economically sustainable models. This model requires that the knee is affordable for patients and clinics. Working with manufacturing and distribution vendors, we aim to have the latest version of ReMotion available for purchase in the second quarter of 2015 at a final retail cost of 80 USD. This price is less than existing low-cost solutions, such as the ICRC knee at over 150 USD (CR Equipments 2013). Clinicians and patients have expressed during our market analysis that this price would be affordable. We have also developed a similar model for phototherapy devices, like Brilliance, as part of our Newborn Health Program. By requiring customers to purchase our products in the marketplace, we aim to ensure that customers are investing in and deriving value from our products.

14.3 Conclusions

14.3.1 Lessons Learned from Field Trials

During the field trials, we learned key lessons about deploying surveys and impact data collection in developing countries.

14.3.1.1 Creating a Survey with Appropriate Context

Originally, we aimed to use standard surveys from the literature that assess the use of prosthetic devices—such as the Trinity Amputation and Prosthesis Experience Scale (TAPES), Locomotor Capabilities Index (LCI), and Functional Measure for Amputees (FMA) (Condie et al. 2006)—so we could easily compare the results of the ReMotion Knee to previous studies of similar devices. However, we quickly learned that many of the questions in these surveys were not appropriate in the context of low-resource settings. For example, some questions referred to golf, hockey, or stepping over curbs, which most patients have not had any experience with, so we modified the surveys to fit the product's intended context. Additionally, as part of the trials we asked patients about their ability and comfort level performing tasks based on previous surveys, especially from the LCI (Grisé et al. 1993). However, it was clear early on that many patients responded that activities were "easy to do alone," creating a ceiling effect with the results. For example, over 85 % of patients responded that it was easy to get up from a chair on their own. We hypothesize that the previous surveys were designed for amputees in the US and Europe, which tends to be an older, less active population. We will need to revise future survey questions accordingly to better reflect the higher activity levels of our target population. We also worked with clinics that had very different capacities in terms of staff and service—from temporary clinics with parachute prosthetists to a large prosthetic school—so we recognized that we needed to develop a survey and protocol that integrated across these different types of clinics.

14.3.1.2 Survey Translation

When translating our survey and instructions from English into each local language, we learned that it is critical to work with our local clinical partners to determine the best translations, as compared to a third-party, formal translator of the language who may not have local and clinical expertise. Our on-the-ground partners not only caught grammatical and translation errors provided from a third-party translator, but each clinic ultimately recommended that the surveys had a mixed translation. Most staff members learn clinical and technical terminology in English, so these terms were kept in English, while more general instructions and questions were translated into the most common local language. This approach to translation remains consistent for technical and clinical data collection across various geographies.

14.3.1.3 Electronic Survey Return

Reliable collection of data and survey results can be a significant challenge for studies distributed across multiple, geographically diverse clinics in resource-limited settings. For these field trials we implemented an electronic survey return system that was surprisingly convenient and reliable for our partner clinics. We set up a secure server for our clinics to upload completed data forms and assigned a single staff member responsibility for submitting the data. This system gave us almost instant access to the results, which greatly reduced risk of the results being lost or destroyed in transit, and allowed us to provide quick feedback to the clinic for any missing information or improvements in recording data. Additionally, by assigning a single staff member, we improved timeliness and consistency in data reporting.

14.3.2 Limitations and Keys for Success

We recognize that our approach will only address the estimated 5–15 % of amputees in developing countries who currently have access to clinics and trained prosthetists (Andrysek 2010; WHO 2011). By utilizing a market-driven approach with an affordable knee joint, we offer clinics the option to charge a rate for prosthetic devices that is both affordable to low-income patients and sustainable for clinics, as it covers their costs of procurement and fitting. While this approach may lead to an increased number of amputees with access to care at existing clinics—and hopefully reduce barriers for other prosthetic devices and components to enter the market—it will not reach amputees who lack access to clinics and trained prosthetists. Reaching these amputees will require investment in prosthetist training, infrastructure improvements, and additional technology development. The International Society for Prosthetics and Orthotics (ISPO) and the WHO report that more than 75 % of all developing countries do not have local training programs for prosthetists (2004). This represents a massive gap between the need for trained personnel and the infrastructure to provide adequate training.

Other factors may limit growth as production and distribution of low-cost prosthetics expands. D-Rev's current approach relies on centralized, third-party distribution that may not be able to efficiently serve rural areas. Countries with high-import tariffs also hinder accessibility to new and low-cost technologies. Other strategies will be required to expand access into more remote areas, such as indirect distribution that would allow regional, independent distributors to purchase knees in bulk and sell directly to end clinics.

14.3.3 A Call for Impact Assessment

Without rigorous long-term, large-scale impact assessment, organizations cannot know if their interventions are effectively improving mobility for disabled populations. Our future impact data collection plans will leverage findings from our more thorough field trial surveys to determine the essential assessments required to understand impact of the knee on a large scale. We aim to understand how effectively the knee remobilizes patients along with psychological and socioeconomic patient benefits. As we introduce the ReMotion Knee onto the market, we will have direct contact with clinics, allowing for continuous data collection and product feedback to promote improved adoption and treatment practices. Our ongoing impact assessment efforts will lead to well-tested protocols for collecting data on the socioeconomic impacts of high-quality prosthetic devices, which will ideally encourage the appropriate prioritization and investment for improved training. By rigorously measuring our efficacy and impact on individual amputees, we aim to become a model for effectively designing and delivering prosthetics components in developing markets. We also strive to remain transparent and accountable for how we collect and report impact by publicly sharing updated data online at www.d-rev.org/impact.

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Chapter 15
Scalable Ecosystem Solution to Screen and Treat Patients with Chronic Infections and Hearing Loss in Emerging Markets

Nicole Leeds, Ruchika Singhal, Jacob Paul and Ananth Annaswamy

Abstract There are 60–330 million patients worldwide suffering from chronic ear infections, with over 90 % of those patients living in the developing world (Acuin Chronic suppurative otitis media: Burden of illness and management options. World Health Organization, Geneva, Switzerland, 2004). More than 75 % of these patients suffer from hearing loss, leading to a significant global disease burden (Acuin Chronic suppurative otitis media: Burden of illness and management options. World Health Organization, Geneva, Switzerland, 2004). The Medtronic Shruti program was designed to address this health burden through a sustainable and scalable model. An ecosystem solution leveraging community health workers (CHWs) is used to screen, diagnose, refer, and treat patients suffering from chronic ear infections. Using an Android phone-based diagnostic kit with customized software and an attached otoscope, CHWs can quickly screen and diagnose patients in a community camp setting. Remote upload of patient information enables ear, nose, and throat (ENT) physicians to monitor and review the diagnosis via Internet. Any infections and hearing loss diagnosed are referred to an ENT physician for treatment and potential surgery. Patients with positive diagnoses have the option of receiving low-cost care at partner hospitals, including medicine-based treatment, audiometric tests, and surgical interventions. Medtronic is in the process of developing a product portfolio designed specifically for low-income, emerging market populations. At the conclusion of the first year, over 40,000 patients have already been screened and 1,900 were treated as part of the program. To date, the program has been implemented in three cities in two countries, with plans to expand across India and into additional emerging markets.

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S. Hostettler et al. (eds.), *Technologies for Development*,
DOI 10.1007/978-3-319-16247-8_15

15.1 Introduction and Purpose

The vision of the Shruti program is to address a significant disease burden and care continuum barriers affecting an underserved population in an emerging market context through the creation of a complete ecosystem of care for patients. Launched in August 2013, the Shruti program is currently a pilot program jointly undertaken by Medtronic, Inc., a world leader in medical device technology and therapies to treat chronic disease, and Dr. Shroff's Charity Eye Hospital (SCEH) in Delhi. Ultimately, the program seeks to address an epidemic of hearing loss caused by chronic ear infections, a condition that affects 65–300 million patients globally, particularly in the developing world (Acuin 2004).

While the Shruti program identifies a wide range of ear-related illnesses identified in screened patients, its particular focus is chronic suppurative otitis media (CSOM), which is a significant cause of preventable hearing loss in the developing world. Ninety percent (90 %) of the cases of CSOM are found in the developing world, and 60 % of those patients suffer from significant hearing impairments that can be treated through ear drainage, antibiotics and antiseptics, or surgery. Ear infections common in early childhood but left untreated heal imperfectly, resulting in a scarred or perforated tympanic membrane (eardrum). As a result, patients can experience a variety of debilitating symptoms, from recurring bouts of mucus discharge lasting from 6 weeks to 3 months, significant hearing loss, or infection. In some cases, the condition can be fatal (Acuin 2004).

The Shruti program was designed to address these chronic ear infections through a sustainable and scalable model which leverages community health workers and an innovative diagnostic kit to identify patients suffering from CSOM and enable them to have access to affordable care. In the current pilot program in Delhi, India, the program has established a pipeline for patients, who are screened by four community health workers trained by SCEH and Medtronic. The health workers are equipped with the ENTraview, a mobile Android phone-based otoscope which is inserted into the patient's ear, allowing the Community Health Worker to examine the eardrum and make simple diagnoses. Any complex infections and hearing loss diagnosed are referred to an ENT surgeon for treatment and potential surgery. Patients with positive diagnosis have the option of receiving low-cost care at local partner clinical facilities, including medicine-based treatment, audiometric tests, and surgical interventions.

The idea for the Shruti program originated in a company-wide effort by Medtronic, Inc. to expand the global reach of its products in new and innovative ways. This effort was particularly focused on emerging markets, the bulk of whose populations had historically been unable to afford Medtronic's high-tech, high-quality product lines. In order to address the needs of emerging markets, Medtronic would need to seek alternatives to these "Premium" products and seek new products and distribution channels that could be used and afforded by a broader segment of the population in an emerging market country.

In an effort to reach out these rapidly-expanding markets, the ear, nose, and throat (ENT) business unit at Medtronic Surgical Technologies began exploring the business cases of previous organizations, such as Aravind Eye Care System and Novartis Social Business Initiatives, whose successful models could be adapted for use in the surgical ENT area. From this initial research phase, the Medtronic team determined five principles that have served as the basis of the Shruti program's design. Ultimately, these five principles are geared toward Shruti's overarching goal of establishing a sustainable business model in an emerging market context:

- Create a Foundation for Scale and Sustainability
- Focus on the Underserved
- Be Willing to Fail and Iterate
- Leverage Partners with Expertise
- Innovate Locally and Frugally

Although early-stage, a successful pilot program for the Shruti model is currently operating in three urban slums in North East Delhi. The first screening camps began in these communities in the fall of 2013, and within its first 6 months the program had successfully screened about 4000 patients, approximately one half of whom were identified with referable ear problems. Ultimately, the Shruti program seeks to use mass screenings to develop a pipeline of patients who, given access to low-cost treatment options, will form a customer base for both new and existing low-cost Medtronic products. In addition to the direct benefit of sale of Medtronic products, a full-scale Shruti program would increase patient flow to existing local healthcare providers, provide a low-cost continuum of care to patients, train and employ local community health workers, and create a range of products that could ultimately be applied to other developing countries as well as to the developed world.

15.2 Program Design

Aware that the scale would be a key driver of a successful and sustainable business model, from the beginning all decisions that informed the design of the current Shruti program were made with the eventual goal of bringing the project to a national and international level scale.

15.2.1 Create a Foundation for Scale

The foundations of the Shruti pilot program were the disease it addressed and the location in which it was launched. Achieving scale would require not only selecting a country with a substantial enough underserved population, but also addressing a medical problem with a high enough incidence of disease to ensure sustainable patient volume. The most important learning from research on other programs was that if Medtronic were to broaden its customer base to include underserved patients in addition to its historical premium product customers, it would need to achieve significant scale to make the venture sustainable and eventually revenue-generating.

The potential to achieve scale was ultimately a question of numbers: identifying a treatable ENT condition in line with Medtronic products that had sufficient disease burden in a given country to warrant a large-scale program investment. To identify a disease with sufficient burden, the Medtronic team used data from a 2009 World Health Organization (WHO) report that compared the incidence of nearly one hundred diseases and other causes of injury and death across its 192 member states. Otitis media emerged in the study as the severest cause of disability in the category of respiratory infections, and India as its location of highest incidence (WHO 2009).

According to the preliminary research, CSOM fit both the necessary characteristics of being (1) related to ENT and Medtronic Surgical Technology's product line and (2) having a high enough incidence to potentially support a Medtronic business infrastructure. The Medtronic team next used CSOM-specific research to identify a country whose population and rates of CSOM could potentially be high enough to ensure an adequate patient pipeline. In 2004, the WHO issued a report on CSOM that classified 27 countries into four groups according to CSOM prevalence. While acknowledging the that existing data on ear infections is incomplete, the WHO report identified six populations with "urgent attention needed to deal with a massive public health problem" caused by the prevalence of CSOM: Tanzania, the Solomon Islands, Guam, Australian Aborigines, Greenland, and India. Of the six countries, India emerged as a market of clear need with an estimated prevalence of 7.8 % (Acuin 2004). When extrapolated to India's population of over one billion people, many of whom are underserved, and coupled with an existing established Medtronic sales presence, it became a clear starting point for the Shruti program.

15.2.2 Focus on the Underserved

In order to reach the nearly 4 billion people that are defined as being "underserved," the Shruti program has to address a variety of barriers to care that affect this population. In Delhi, the Shruti team identified six primary factors that inhibited patients from seeking care for their ear infections. These barriers included: lack of awareness about the disease and the potential for treatment, seeking and using home remedies that resulted in additional harm to the patient, the lack of a referral pathway to a pediatrician or ENT who could diagnose the problem, lack of access to specialists to treat the problem, the cost of care, and finally long-term management and follow-up after treatment.

To address these barriers, the Shruti team needed to design a continuum of care that would not only create a pipeline of patients in need of surgery, for which there were existing Medtronic products, but could also provide access to the procedures

Barriers in Continuum of Care Addressed

	Screening	Wax Removal	Diagnosis	Referral to Partner Hospital	Referral to specialist
Barrier(s) Addressed	• Lack of Awareness • Harmful Home Remedies	• Harmful Home Remedies	• Preferred Pathway to ENT (via internet) • Cost of Care	• Preferred Pathway to ENT • Cost of Care • Management & Follow-Up	• Access to Specialist • Cost of Care • Management & Follow up
Health Care Worker	CHW	CHW	CHW/ENT	ENT	Specialist
Location	Community Camp	Community Camp	Community Camp	Partner hospital	Partner hospital

Fig. 15.1 The Shruti model, developed in partnership with Dr. Shroff Charity Eye Hospital (SCEH), aimed to address the barriers to care that underserved CSOM patients faced by providing healthcare triage and treatment by the appropriate healthcare worker in an accessible setting

or treatments that patients with nonsurgical cases of CSOM may require. To test the model, SCEH and Medtronic worked together to create a clear pathway for patients from disease awareness to long-term treatment. This pathway, illustrated in Fig. 15.1, mapped patient's needs against the appropriate healthcare specialist and care location to best address these barriers. Eventually, the program aimed to develop products that could be added to this continuum to further reduce cost and increase treatment options for the patient population.

By providing a clear pathway to care offered entirely through SCEH, the Shruti team was able to monitor each aspect of a patient's care from the time they first became aware of the disease through the final stages of treatment, creating a self-contained ecosystem in which to pilot the program. By tracking patient data and follow-up, the Shruti team was able to determine at which stages patients did not access care post-diagnosis, gathering key information on which elements of the program would need to be adapted if it was to bring care to a larger number of underserved patients.

15.2.3 Be Willing to Fail and Iterate

A key aspect of the Shruti program's path to scale is willingness to develop new program models and products, but also to test and refine them as the program progresses. The pilot program in conjunction with SCEH was developed as a means of testing the program's feasibility, offering proof of concept in an enclosed ecosystem before considering a larger-scale program involving more partners and patients.

While the program is still in early stages, the initial data offers a more detailed picture of how to refine the model to increase access for patients before seeking to scale it. The first iteration of the model was immediately successful in some respects: for example, the program has greatly reduced the barrier of cost to the patient by making the initial screening and diagnosis free of charge, and by offering surgery at the cost of 3500 rupees per ear (approximately US$60), an affordable level for most patients in this demographic. In addition to cost savings, the free screenings allowed patients who had no regular access to physicians to be informed up-front and free of charge about the treatment plans available to them, which significantly eased barriers to care because patients were able to seek treatment without concern that they would be wasting time and money on visits to the hospital for an untreatable condition or for an unaffordable procedure. It also meant that patients whose ailments were treatable were able to assemble the needed financial resources before visiting the hospital, cutting down on unnecessary visits and increasing the efficiency of specialist time.

While the pilot program showed immediate success in addressing some of the barriers to care, it also highlighted challenges that the Shruti program will need to address in order to bring the project to scale. For example, while the current cost to the patient is affordable to most in the demographic, the time needed for hospital visits and surgeries is a significant strain on patients who depend on hourly income. As a result, the majority of patients who have successfully undergone surgery have been women and children who are not the family's primary breadwinners. Increasing hospital efficiency in handling these patients would lower this barrier to care as well as allow specialists to see more patients.

15.2.4 Leverage Partners with Expertise

The Shruti program relies on partnerships to make the program sustainable and scalable. While Medtronic brought expertise in the development of surgical technologies and over 30 years of experience with direct sales in India to the Shruti program, both operational and technology innovation partners have been key to patient outreach and care as well as to developing the right products for the program and population. At each phase of the program's development, partners have been and will continue to be the key to operating and scaling successfully.

The original concept and model for the Shruti program was developed in partnership with The Society for Sound Hearing, which facilitated the initial introduction between Medtronic and SCEH, and their existing community-focused tools and expertise catalyzed the community research process.

The partnership between Shroff and Medtronic allowed the Shruti pilot to become operational quickly and at low-cost. Medtronic sponsorship, connections, and technological expertise lowered the barriers to a quick start-up, including the development of the diagnostic kit and software needed for mass screenings. The hospital's existing infrastructure was the initial basis of the partnership, but SCEH's connections in the target communities became invaluable to a rapid launch as it was able to quickly recruit and train the five necessary community health workers

(CHWs), launch screening camps, and develop the educational pamphlets and materials that would keep patients informed about the program. SCEH and its staff provided the continuum of care that brought patients into the hospital and made the Shruti program operational.

In addition to operations, partnerships have also been key to developing the Shruti Ear Screening Kit, the diagnostic kit that has formed the basis of the Shruti program to date. Consisting of a mobile Android phone-based otoscope with a light source and a SIM data card working on rechargeable batteries, the kit enables the community health workers to view the eardrum and diagnose the majority of infections that affect it. The kit was developed in partnership with Icarus Design, a design consultancy based in Bangalore.

The hardware designed by Icarus works in conjunction with a customized software application developed by ClickMedix for the kit. Like other Shruti partners, ClickMedix is an expert in working with underserved populations, particularly through the use of mobile technologies and community health workers to better connect patients and physicians. ClickMedix developed the program to capture patient information and aid the community health worker in making simple diagnoses through visualization of the tympanic membrane on the android phone. The software also allows for a remote upload of patient information, which enables ENT physicians to monitor and review the diagnosis via Internet.

The success of the first 6 months of the pilot program has led an additional partnership with the Health Management and Research Institute aimed at increasing geographic reach and patient numbers through an expansion to southern India. HMRI, an expert in providing high-quality, low-cost healthcare to vulnerable populations by offering services that are integrated with India's existing healthcare system and resources.

15.2.5 Innovate Locally and Frugally

Related to the primacy of partnership is the need for new products designed for the local context in which they would be used. From the outset of the emerging market strategy it was clear that some of Medtronic's key current products for the Shruti program would make the cost of care too high for most patients in its target market. While philanthropic donations of equipment could assist partner hospitals in the short term, failure to address this issue would present a significant barrier to scale in the long run. Product development at Medtronic in the United States was an option, but the willingness and ability to invest in products specifically designed for the local context and price point needed for scale.

The creation of the Shruti Ear Screening Kit was a prime example of local and frugal innovation at work. Designed in conjunction with Icarus and an ENT physician at Shroff, the screening device is extremely effective, easy to use, and low-cost.

15.3 Results

The first 6 months of the pilot program have provided proof of concept for the Shruti model by proving the ability to create an ecosystem solution to the diagnosis and treatment of ear infections. As of January 2014, the program had established a successful pipeline of patients from screening to surgery, with over 3,700 patients screened in the first 6 months of the pilot.

Of the patients screened, 577 (approximately 15 %) received preliminary diagnoses and referrals to SCEH for care. At the time of writing, 25 % of those patients who received referrals registered for care at SCEH.

To date, the pilot program at SCEH has confirmed that there is an existing market for low-cost interventions for CSOM by confirming population need and interest, guiding the creation and testing a successful diagnostic product, and validating the patient pipeline and continuum of care established by the Shruti program.

15.4 Conclusions

While the preliminary results of the pilot program have been satisfactory, they have also helped to identify some key learnings around the most important barriers to scale that the Shruti program will need to address if it is to reach its target scale of screening 100 million patients. These learnings are applicable not only to the Shruti program, but also to others seeking to create a sustainable business model in an emerging market.

15.4.1 Focus on the Disease, Not the Product

In order to design a product that is truly suited to the needs of the market, Medtronic chose to focus its efforts on eliminating a specific problem already identified, without allegiance to a specific product. This flexibility was key to the program value of being willing to fail and iterate, as the expected equipment or treatment is not always the same between countries, regions, and market types.

In the case of the Shruti program, the original research clearly indicated the prevalence of CSOM, and the Medtronic team's original plan was to address the problem using vent tubes, a simple and relatively inexpensive surgery common in the United States to treat otitis media by inserting a small tube into the eardrum while the patient is under anesthesia to release pressure behind the tympanic membrane. However, while the Shruti team saw prevalence rates comparable to those in the research, they found that most cases they encountered in India were so advanced that the membrane was already ruptured and could not be treated with vent tubes. As a result, the team has shifted its focus away from vent tubes, which were already a part of the Medtronic product line, and toward the acquisition or development of new products better suited to the environment, such as surgical tools for tympanoplasties and mastoidectomies. This flexibility to seek new products and to reinvent the program in response to actual observations from the field is critical to addressing problems before they are scaled.

15.4.2 Partner with Others to Develop a Sustainable Ecosystem of Care

Even with Medtronic's long history in India, each step of the development of the Shruti program has been done in conjunction with local partners who are experts in their fields and who also have a stake in the success of the program. While charitable initiatives have addressed many public health problems in the past, their dependency on other sources for funding makes them vulnerable. While some initial plans for a Medtronic expansion into India involved a full spectrum of care administered by Medtronic, including community health workers and clinics, the partnerships that have characterized the Shruti program have significantly decreased the program's start-up time through their expertise and infrastructure in design, operations, and clinical work that Medtronic did not possess.

The Shruti program covers an entire continuum of care, from product design, testing, and deployment to screening to treatment to long-term follow-up. Few organizations have expertise in all these areas, and in order to stay focused on its own areas of strength Medtronic has worked with others on the operation and innovative portions of the project. Planned future partnerships will help Shruti's local presence as it seeks to expand to state government hospitals to reach scale.

For example, SCEH's knowledge of and connections into the community that Shruti seeks to serve allowed them to recruit, train, and deploy CHWs into quickly-organized camps within a few weeks, without a prolonged hiring or organizational process. Particularly in the case of the screening camps, bureaucracy and organization can take weeks for a new player, but SCEH's reputation and community knowledge allowed them to open camps that successfully attracted hundreds of patients with only a few days' notice.

Beyond providing expertise in the initial stages of the program, partners who share in the profits of the program are key to sustainability in the long run. For SCEH, increased patient flow to the hospital is a direct benefit of its participation in the Shruti program. For other patient populations in other cities, partnerships with government hospitals, privately practicing ENTs, and even the CHWs themselves will need to be designed to benefit them enough to keep their stage in the Shruti program going.

Partners have helped Medtronic at every level of the program's growth and will continue to be a key part of the Shruti program as it expands. While past partnerships have been primarily with nongovernmental organizations and private partners, as the Shruti program begins to work with private ENTs and governmental hospitals the range and scale of partnerships will continue to grow.

15.4.3 Ensure Visibility and Involvement of Senior Leadership

The strong support of senior leadership from within Medtronic's organization has been essential from the program's inception and will continue to be a vital component of Shruti's growth and development. Emerging market programs, and particularly those programs targeting underserved populations, are by nature risky and require long-term investments over several years before and if they become profitable. Beyond their obvious benefits, strong support from the highest level of the company as well as the financial commitment necessary to sustain the program for several years helps foster a culture of innovation and risk-taking, an entrepreneurial mindset necessary to developing these programs. Moreover, in companies that have a significant domestic focus it also helps to prioritize what may be seen as a very secondary project to the growth and development on the US side. For this reason, developing an emerging market project like the Shruti program is possible only with championship and funding from the company's highest levels.

15.4.4 Cultivate and Maintain an Entrepreneurial Mindset

Related to the importance of senior leadership involvement is the necessity of maintaining an entrepreneurial mindset, where a lean team is able to make decisions quickly and without bureaucracy. Particularly in already established organizations seeking to expand into new markets, maintaining an atmosphere in which team members feel empowered to make decisions without the burden of a heavy hierarchy and to feel supported by their leadership through the inevitable mistakes that will occur over a program's launch is essential to a high-functioning, risk-taking, adaptable team mentality necessary to operate in an emerging market space.

In conclusion, as the Shruti program seeks to grow and refine its model over the coming years, its sustainability, effectiveness, and profitability at scale will depend on its ability to adapt to the reality of markets in India and to the support it can garner and maintain from internal Medtronic leadership and external partners, and stakeholders. Having identified a critical public health problem and an underserved market for treatment, as well as a preliminary solution for treating it, the Shruti team will turn its attention to three critical challenges to scale. First, the broadening of Shruti's geographical and stakeholder reach through an expansion to government hospitals in Hyderabad, a project that will begin in February 2014. Second, and perhaps more urgently, the development of additional affordable, effective models to treat the long-term damage that patients have suffered due to CSOM. With these elements in place, Shruti will make enormous strides toward its eventual goal of screening 100 million patients.

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Part V
Impact Assessment of Technologies for Development

Chapter 16
Tools to Measure the Development Impact of Innovations

Ashok J. Gadgil and Temina Madon

Abstract Measuring the social and economic impacts of a product or service is a challenge in any context, but particularly among low-income communities. These contexts often lack the infrastructure, institutions, and investment required to assess the long-term benefits and risks of a new healthcare device, sanitation solution, or irrigation technology. Recent innovations in measurement are addressing this challenge. Increasingly, researchers are using sensors, satellites, and mobile platforms to automatically or remotely capture rich, finely resolved data from households and communities. There also is growing use of field experiments—adapted from clinical science—to study the changes introduced by a product's distribution and use. These tools and techniques are enabling researchers to credibly demonstrate the outcomes of development interventions; they are also generating durable lessons about household demand for products and services. More broadly, they inform the process of technology innovation for development—by providing insights into what works, and what does not.

16.1 Introduction

Technological innovations can dramatically improve development outcomes. A recent example is the rapid expansion of mobile telephony in India, which has driven market efficiencies and income growth among the poorest households (Jensen 2007). Yet few technologies have been able to match the scale and impact

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S. Hostettler et al. (eds.), *Technologies for Development*,
DOI 10.1007/978-3-319-16247-8_16

of mobile phones. Some innovations fail altogether. Take, for example, the proliferation of handpump-attached arsenic treatment units in West Bengal. In a study of more than 100 improved water pumps in the region, nearly all had become defunct within a year of installation (Das and Roy 2014). Such failures are far more common than successes. Why do we so often fail to produce technologies with development impact?

To design for low-resource communities, researchers need to understand the environment in which the technology will be expected to perform. This includes accommodating consumer preferences and existing work practices. Researchers also must have a clear map of the economic, social, and environmental barriers to profitable use of a new technology. Mechanisms for delivery and maintenance must be designed. Careful feedback must be obtained during prototyping, to understand and fix failures not observed in laboratory settings. All this is essential to ensure sustainable access and adoption.

Indeed there is little room for error, because impoverished households have scarce time and effort to invest in technologies that are not productive, welfare-improving, or labor-saving.

The central challenge is that a technology's performance in the field—and, indeed, the benefits of a new technology—can be difficult to measure in developing countries. Low-resource settings often lack the tools used in wealthier countries to understand consumer response (including computerized receipts, utility meters, web traffic logs, and representative household surveys). As an alternative, engineers and practitioners have traditionally relied on small-scale, infrequent surveys and focus groups to measure self-reported user experiences. However, these methods can be costly to implement, and they are prone to bias and measurement errors (Bound et al. 2001).

Recent scientific advances are addressing this challenge. Emerging technologies—from low-cost mobile devices and wireless sensors, to improved network protocols and remote sensing techniques—have enabled researchers to capture massive amounts of data in the field. It is now feasible, even in the most remote areas, to gather reliable indicators for market activity, environmental change, and human behavior. In tandem, advances in applied statistics (including the use of randomized controlled trials in field settings) have made it possible to rigorously evaluate the long-term social impacts of interventions. Development economists, in particular, have adapted clinical trial methodologies for the complex, less controlled conditions outside the medical clinic (Duflo et al. 2007). Together, these new approaches have the potential to revolutionize the way that pro-poor technologies are designed.

For example, the designers of clean water technologies can now make empirical estimates of household "willingness to pay" for a new product or service, using experimental methods rather than models or assumptions (Kremer et al. 2011). In willingness-to-pay experiments, households within a given market area are entered into a lottery. Each receives a coupon, selected at random, representing one of several different discount rates (e.g., 0, 10, 30, 50%, or 70 %). The new product is then introduced into the market. By tracking which coupons are redeemed, it is possible to trace out a demand curve showing the purchase rate at each price point.

This information is more reliable than stated willingness to pay, as it simulates the natural market environment (Dupas 2014). Results from these studies can be used to set the final cost parameters for a product, including the costs of distribution.

Multi-arm randomized trials are another useful tool for prototyping. In each arm of the trial, a slightly different product is offered. Differential take-up across the study arms can reveal which features of a product are most useful. In the parlance of software development, this strategy is known as A/B testing, and it can accelerate the pace of prototyping. The approach can be combined with improved measurement instruments (like wireless sensors or low-power meters) to automate user data collection and reduce the costs of experimentation. Advanced measurement instruments are now being used to track the performance and use of low-cost cookstoves (Ruiz-Mercado et al. 2011), latrines (Clasen et al. 2012), water pumps (Thomas et al. 2013), educational technologies (Chang et al. 2014), and a range of other innovations for the poor.

The papers in this section (Part V) investigate the impacts of technologies along the entire arc of product design. Once a problem has been defined, it is important to assess existing technologies in the space, revealing the unmet needs of users and suppliers. Here, Olschewski et al. (Chap. 18) contribute a useful framework for mapping the social, economic, and environmental hurdles faced by any new technology. The authors use the WASH sector as an example, detailing challenges in the supply and demand sides of 13 different innovations. They also consider the institutional actors involved in technology markets (including regulators and policymakers). The impact of any new technology will hinge on careful thinking, upfront, about the concepts outlined in this report.

Next we turn to the prototyping of solutions for development challenges. Rahgu et al. (Chap. 19) report on the early-stage prototyping of an mHealth application for management of cardiovascular disease in India. They demonstrate how user-centered design and frequent feedback is used to refine a smartphone-based clinical decision tool. The authors capture information about accessibility of the app by interviewing physician users; they also analyze server logs, which automatically generate performance data during use. Increasingly, software developers are instrumenting code to automatically capture performance and use data. This is a promising area for further research (Alspaugh et al. 2014).

At this stage in product development, it is important to design and prototype the supply mechanisms for a new technology, since impact relies on sustained access. The innovation must also be optimized for adoption by the end-user. This is one of the greatest unmet challenges in technology for development. Too often, unanticipated market failures or behavioral barriers prevent technology delivery and adoption.

Adoption is the focus of Wilson et al. (Chap. 20), who report on the use of an improved cookstove by women in Sudan. Their report is part of an ongoing effort to design a high-efficiency cookstove distributed through local, sustainable sales channels. The team uses both surveys and temperature dataloggers to expose the dynamics of stove use over many weeks. In this case, active use of the stove is essentially a proxy for impact, since the health and economic benefits of the technology require sustained (and substantial) use of the stove.

The study finds that in interviews, women over-report cooking events nearly two-fold relative to sensor measurements. In addition, a significant proportion of women fail to use the stove at all. This suggests the need for understanding the users better, and designing improvements in the stoves' distribution methods. By directly measuring user behavior in a natural environment, researchers can pinpoint the features needed to facilitate take-up and impact of a potentially transformative technology.

Ultimately, technology for development must achieve some impact on user welfare, growth, and resilience. Randomized controlled trials are a standard method for rigorously evaluating impact, particularly when the outcomes of interest (like health, education, or income) are downstream from the new technology. This approach can reveal unanticipated failures, measure end-user benefits, and identify opportunities for further improvement.

Finally, once an intervention or technology is distributed and adopted, it useful to have a tool for long-term monitoring of outcomes. This is akin to the post-market surveillance conducted by pharmaceutical companies, after they have released an approved drug or device at full scale. Remote monitoring of development outcomes is the focus of the paper by Beech et al. (Chap. 17).

In summary, there is a suite of scientific advances that have made it far more feasible to measure the impact of development innovations, along the entire arc of product development. These include:

- **Measurement Technology**: The instrumentation of products with low-power, unobtrusive sensors or meters can be used to characterize adoption, use patterns, and changes in behavior over time. Examples include meters that capture household-level use of new electricity solutions in rural settings, or sensors to measure indoor air pollution in households with and without improved cookstoves.
- **User Analytics**: Digital data from mobile telephony, electronic payments, and identity authentication systems can be used to understand the impacts of these services, and to study variations in design. This approach essentially uses data by-products to capture useful information about consumers. Examples include the analysis of mobile phone data to understand response to a natural disaster or disease epidemic, or the instrumentation of software services that leverage consumer devices as a platform.
- **Field Trials**: Economic experiments (e.g., randomized controlled trials) are increasingly used to estimate the impacts of new technologies, in real world settings. Examples include experiments measuring willingness to pay for a new technology or feature, as well as studies of changes in welfare that result from adoption of a new device or service.

Of necessity, it is essential for researchers and designers to carefully consider the privacy and ethical concerns raised by impact measurement—from the ethics of using unobtrusive sensors to track human behavior, to the use of randomized trials, to the protection of personal information in large-scale data analytics. This is an important concern at the frontier in technology for development and warrants further exploration.

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Chapter 17
Toward a Spatial Monitoring and Evaluation System, Collecting Indicators to Map and Measure

Craig Beech, Marina Faber, Arlene Herbst and Denton Joachim

Abstract Peace Parks Foundation (PPF) facilitates the establishment of transboundary protected areas in southern Africa. Focus is on ten Transfrontier Conservation Areas (TFCAs) contributing over 60 million hectares toward conservation estate. Stakeholders of the TFCA process include government officials, wildlife agencies, private entities, and local communities. To advocate, plan and manage TFCAs, emphasis is placed on spatial planning. Timeous information sharing and reporting is paramount to the process. geoMEtri, an add-in residing in ArcGIS Explorer, was developed by PPF as a result of the identified need for collecting standardized spatial data indicators for effective management and decision support. geoMEtri provides for the capture of indicators across various disciplines including human–wildlife conflict; crimes against wildlife; species observations; socioeconomic indicators; marine monitoring; as well as various management and infrastructure-related aspects, such as alien plant management and weather recordings. To ease the work flow, the system allows for direct importation of Global Positioning System (GPS) data. geoMEtri databases are backed-up and can be shared among users of the software. A central data repository operates as the hub for all incoming data and the redistribution thereof. Process models are used to analyze data which are incorporated into map services which in turn can be consumed by the users of the software with an internet connection. Reporting of data is also offered in various formats, all geared to be visual and succinct. Offering standardized tools to all stakeholders in TFCAs and proposing a means of data collection, information management, and knowledge-based results goes a long way toward alleviating misperceptions which may exist between land use options. As technologies merge toward a connected environment based around the use of smart devices, combined with crowdsourcing a very exciting future exists for leveraging data and information capture and the sharing of these results via effective reporting tools. geoMEtri is in the process of being engineered for Android and iOS mobile platforms.

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S. Hostettler et al. (eds.), *Technologies for Development*,
DOI 10.1007/978-3-319-16247-8_17

17.1 Introduction and Purpose

For 15 years Peace Parks Foundation (PPF) has facilitated the establishment of transboundary protected areas in southern Africa. Focus is on ten Transfrontier Conservation Areas (TFCAs) straddling 11 countries and contributing over 60 million hectares toward conservation estate in the region (Fig. 17.1).

On 27 May 1990, Anton Rupert, President of WWF South Africa (then called the Southern African Nature Foundation) had a meeting in Maputo with Mozambique's President Joaquim Chissano, to discuss the possibility of establishing a permanent link between some of the protected areas in southern Mozambique and their adjacent counterparts in South Africa, Swaziland, and Zimbabwe.

The concept of transborder protected area cooperation through the establishment of peace parks had already been accepted internationally. The World Conservation Union (IUCN) had long been promoting their establishment because of the many associated benefits (Hamilton 1996; Westing 1993). In 1988, the IUCN's Commission on National Parks and Protected Areas had identified at least 70 protected areas in 65 countries which straddle national frontiers (Thorsell 1990). As a result of Rupert's meeting, the World Wildlife Fund for Nature (WWF) in South Africa was requested to carry out a feasibility study, which was completed and submitted to the Government of Mozambique in September 1991 (Tinley and van Riet 1991). The report was discussed by the Mozambican Council of Ministers, who

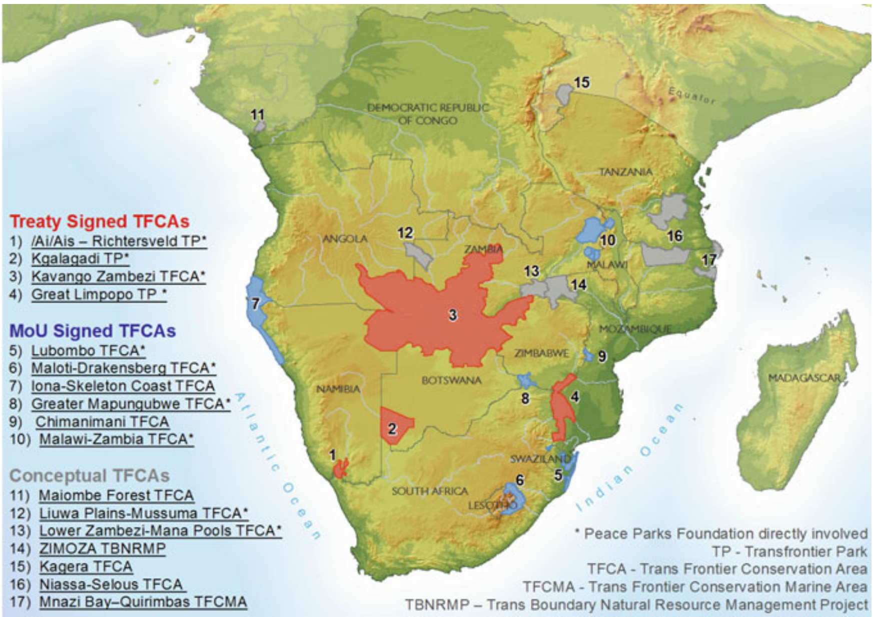

Fig. 17.1 A map indicating the 17 Terrestrial TFCAs in southern Africa, ten of which are worked in by PPF

recommended further studies to assess fully the political, socioeconomic, and ecological aspects of the feasibility study. The Government of Mozambique then requested the Global Environment Facility (GEF) of The World Bank to provide assistance for the project, which was granted. The first mission was fielded in 1991, and in June 1996 The World Bank released its recommendation in a report entitled Mozambique: TFCAs Pilot and Institutional Strengthening Project (World Bank 1996). The report suggested an important conceptual shift away from the idea of strictly protected national parks toward greater emphasis on multiple resource use by local communities by introducing the TFCA concept. In short, TFCAs (or peace parks), were defined as relatively large areas that straddle frontiers between two or more countries and cover large-scale natural systems encompassing one or more protected areas. Very often both human and animal populations traditionally migrated across or straddled the political boundaries concerned. In essence, TFCAs therefore extend far beyond designated protected areas, and can incorporate such innovative approaches as biosphere reserves and a wide range of community-based natural resource management programmes (World Bank 1996). PPF subsequently adopted this new paradigm.

Toward the end of 1996, it became clear that interest in the peace park concept was not only growing within the countries mentioned, but also in other neighboring states. For the first time, southern Africa as a whole was being seen as a tourist destination, and an integral part of this vision was the development of TFCAs or peace parks. There was a growing recognition that tourism could be the one industry with the potential to become the economic engine that would create the jobs that were so urgently needed on the subcontinent.

It is important to note that internationally, the United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC) drew up an inventory in 2007, based on reviewing the digital maps of the World Database on Protected Areas (WDPA) and identified 227 transboundary protected area (TBPA) complexes incorporating 3043 individual protected areas or internationally designated sites (Lysenko et al. 2007).

A strong emphasis is placed on spatial planning to advocate, plan, and manage TFCAs. Much data and information is needed when planning a landscape wide level land use mosaic, which is common in TFCAs. Stakeholders of the TFCA process include government officials, wildlife agencies, private entities, and local communities. Timeous information sharing and reporting is paramount. Due to working in so many countries and with so many partners across disciplines there was a need to design and develop a system which would be used to collect standardized data indicators for effective management and decision support throughout the programmes and projects in the region.

The collection of these data indicators, ultimately, is to build data, information, and knowledge for effective monitoring of the various activities which are important in TFCAs. The continuous collection of data indicators over time allows for the identification of trends in the TFCA's status and its activities and management processes, consequently fostering adaptive management practices.

When collecting indicators, these need to be: Specific, Measurable; Achievable, Relevant, and Time-bound (S.M.A.R.T.). These are adopted from best-known global practices (Doran 1981), criteria of the well-known mnemonic SMART. PPF has, however, very importantly added SMARTS, the plural, to the collection of these indicators with the objective of making each and every indicator Spatial, and therefore mappable—allowing for their use and inclusion into a geographical information system (GIS). Furthermore, the indicators being collected need to be Precise—allowing for each to be defined in the same way by all people; Consistent—by definition not to change over time; and Sensitive—to have the measured indicator respond proportionally to actual changes.

17.2 Design and Method

17.2.1 The System

ArcGIS Explorer is a user-friendly GIS (ESRI 2013) and it is freeware. geoMEtri is a customized software database residing within this GIS platform as an Add-In. PPF has spent the past six years engaging local authorities, agencies, researchers, and local community members toward adapting this software into a tool which collects spatial and temporal data.

Managing data is a complex and challenging endeavor. As much data is sourced from various regions and with varying temporal scales, it is necessary to ensure that the system by which this data is managed is robust and effective. An Enterprise GIS can be defined as a centralized database that every department in the organization, (or in this case many organizations and agencies) contributes to and shares (Tang and Selwood 2003; Thomas 2009). Data management is further complicated by allowing for crowdsourcing and having members of the "crowd" feeding into this system. By registering into the database with varied levels of competency, it allows for the first level of data verification. Incoming data based on expertise and known users can allow for a filtration of the data in the enterprise system to be further filtered through various quality assessments and control mechanisms.

Geodatabases offer advantages over other spatial data formats, allowing for spatially dependent features classes to be more organized and manageable. These include the use of domains, which are valid values or ranges of values for an attribute field and minimizes data entry mistakes as well as prohibiting invalid entries (Ormsby et al. 2001).

17.2.2 Data Capture

The geoMEtri software is designed to operate in a hierarchical fashion, whereby an Operation needs to be defined to plan and design the field work which is to be

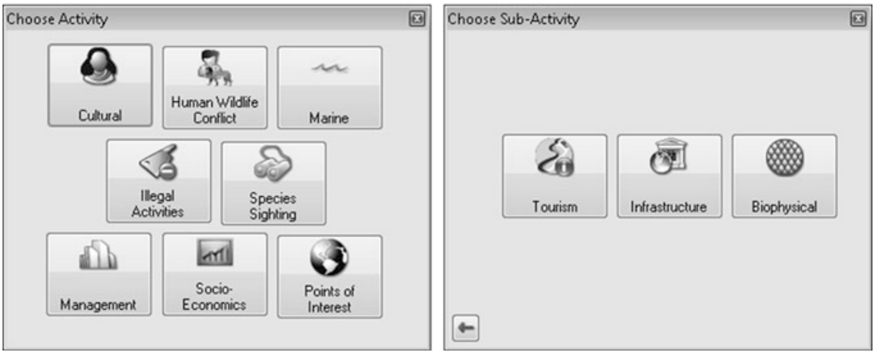

Fig. 17.2 Illustration of the current *Activities* and *Subactivities* (of Points of Interest) which can be captured into predefined *Operations* during field work

undertaken. Each Operation in turn can have one or more activities which will allow for data collection for that specific Operation. Some of the Activities have Subactivities which allow for easier management and categorization of field data collection (Fig. 17.2).

Activities which are included within geoMEtri, and monitored using spatial and temporal indicators include human–wildlife conflict; crimes against wildlife; species observations; socioeconomic indicators; marine monitoring; management matters and points of interest. Global Positioning System (GPS) receivers are used to collect the locations of the activities—use of GPS receivers is a way of accurately determining positions on the earth surface (Steede-Terry 2000). PPF identify key "champions" to make use of geoMEtri to "tag" GPS data with value-added information (*Activities* and *Subactivities*). The system makes use of both paper-based and digital means of data capture. Paper forms which are used in the field have been designed to replicate and ease the input of data via the application's digital forms. These alternatives are offered due to limitations of suitable hardware and lack of infrastructure in several project sites. Accuracy is important, and to ease the work flow process, the system allows for direct importation of GPS data. Furthermore, tagging of information within the geoMEtri system is standardized through the capture of predefined dropdown and selection boxes. Species names are also contained within the database and as a result, data capture errors are minimized.

17.2.3 Work Flow

Due to the many challenges such as the lack of power and internet connectivity in the field in many of the project areas, the current work flow includes the use of GPS handheld devices, and paper-based capture forms. A GPS point is marked and numbered and the form is then completed relating back to the activities as listed

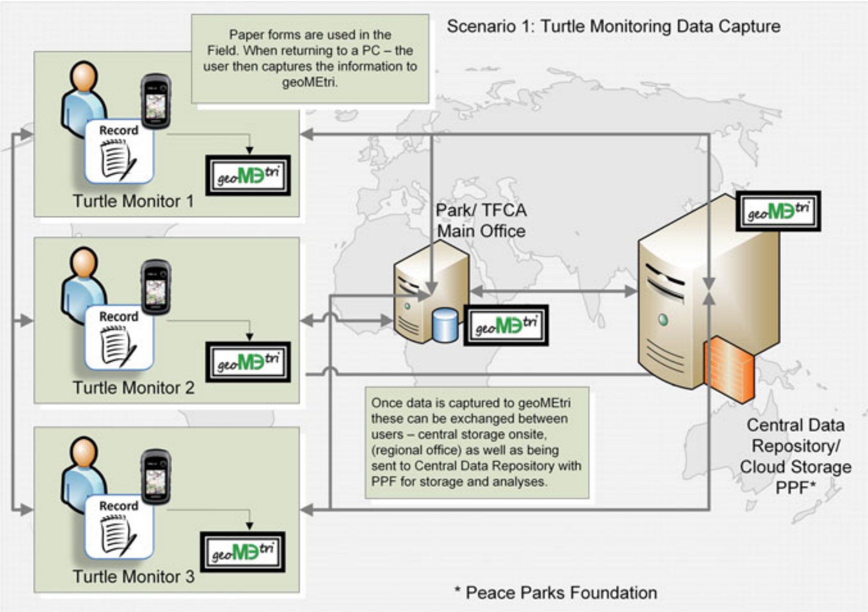

Fig. 17.3 The Scenario, as used by turtle monitors in Mozambique to record data and information related to turtle nesting sites. Data is captured in the field using forms and GPS receivers, and once entered into geoMEtri the flow of information between users, regional and central data storage is illustrated

herein above. Each activity contains fields—metatags—which are specific and relevant to that activity. These have been derived through years of stakeholder engagement to determine the minimum data which is to be captured within time limitations which can support planning, management, and monitoring work.

Field officers, once back in an office environment, can then capture the field form information into their geoMEtri application residing within the ArcGIS Explorer software. GPS data is downloaded in GPX file format. These are in turn imported into geoMEtri via ArcGIS Explorer and immediately tagged to which *Operation* and which *Activity* within that *Operation* the spatial point is associated. Once captured into the system, colleagues can exchange and augment their databases by sharing exported geoMEtri backup files. Similarly, these shareable file formats, all light-weight text files can also then be sent through to the central repository for data verification, processing, and spatial analyzing (Fig. 17.3).

17.2.4 Standardization

The database and capture forms are designed to standardize data input, and to allow for the association of information (metatags) to each data point by allowing the user

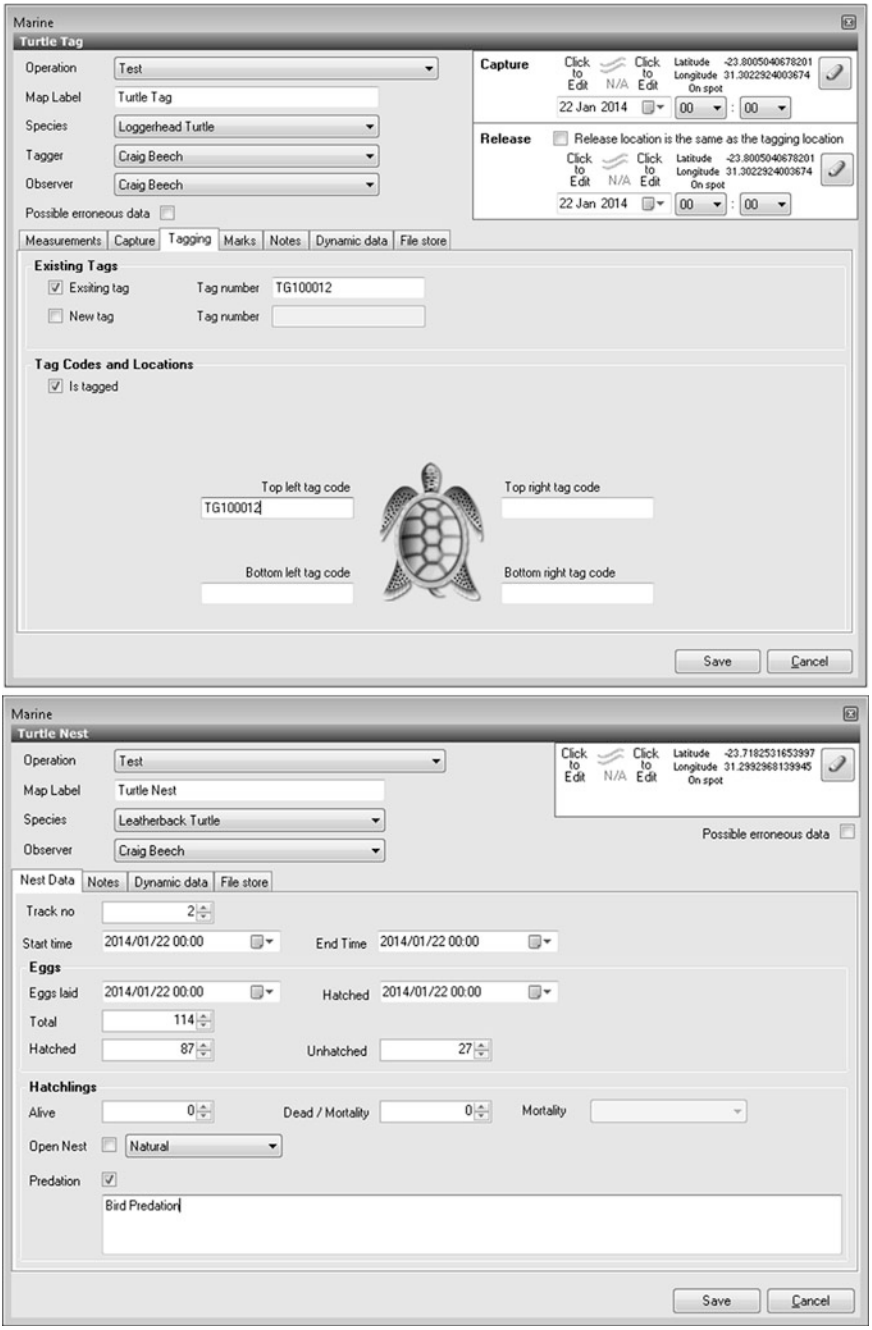

Fig. 17.4 Data capture forms illustrating the standardization and association of information (metatags) to the GPS data which has been imported into geoMEtri

to select, rather than manually input the information. Metatags not only include the basics such as date and time, but allow for other conditions to be captured. If for example monitoring species, the species name is selected from a database,[1] both scientific and common names, thereby preventing spelling and other erroneous data input. Information related to the observation is then selected from various tabs, fields, and checklists within the data form (Fig. 17.4).

17.3 Results

For the users of the software, mapped results are immediately displayed as point symbol locations within ArcGIS Explorer, where various underlying datasets such as satellite imagery, topographic maps, or any GIS data format, offers a foundation for users to contextualize their data locations. These data can be queried and scrutinized as would any spatial and attribute information in a GIS.

Because of the structure and integrity of the database and application design, geoMEtri databases can easily be shared and exchanged between users. The backup cached files are sent to a central data repository, where all incoming data is collected and verified for analytical and mapping purposes.

Each user of the application has immediate access to visualize their own data capture efforts as point layers overlaid in ArcGIS Explorer. Reporting of data is also offered in various formats, all geared to be visual and succinct. Maps can be printed and used to augment mandatory reporting within organizations. Management is also able to quickly and effectively obtain data from all users within their organization, compare work efforts, and adopt an adaptive management practice.

Futhermore, geoMEtri operates on two access levels. The first is a direct connection to the central repository, directly feeding this database with the respective field data. This is not the preferred means of the work flow, due to erroneous incoming data and data security. For this reason, this is a hidden functionality only accessible to administrative users. The second and preferred means of data exchange is via compressed geoMEtri backup files, created by export and import from and to the applications and server-side, respectively.

Once the compressed geoMEtri backup file has been sent to the central data repository (PPF Head Office) and integrated into the spatial data engine, process models run these incoming point data, using their spatial reference and attribute information to produce various surface layers, for example heat/density maps. Close-to-real-time GIS analyzed results are offered back to the end user, in a connected environment. The resultant analyses in the form of GIS layers are then served as map services with the updated information back to the end user when an internet connection is made. Figure 17.5 shows an example of turtle nesting site densities, processed, and analyzed using advanced licensed GIS software.

[1]Catalogue of Life Database. http://www.catalogueoflife.org/.

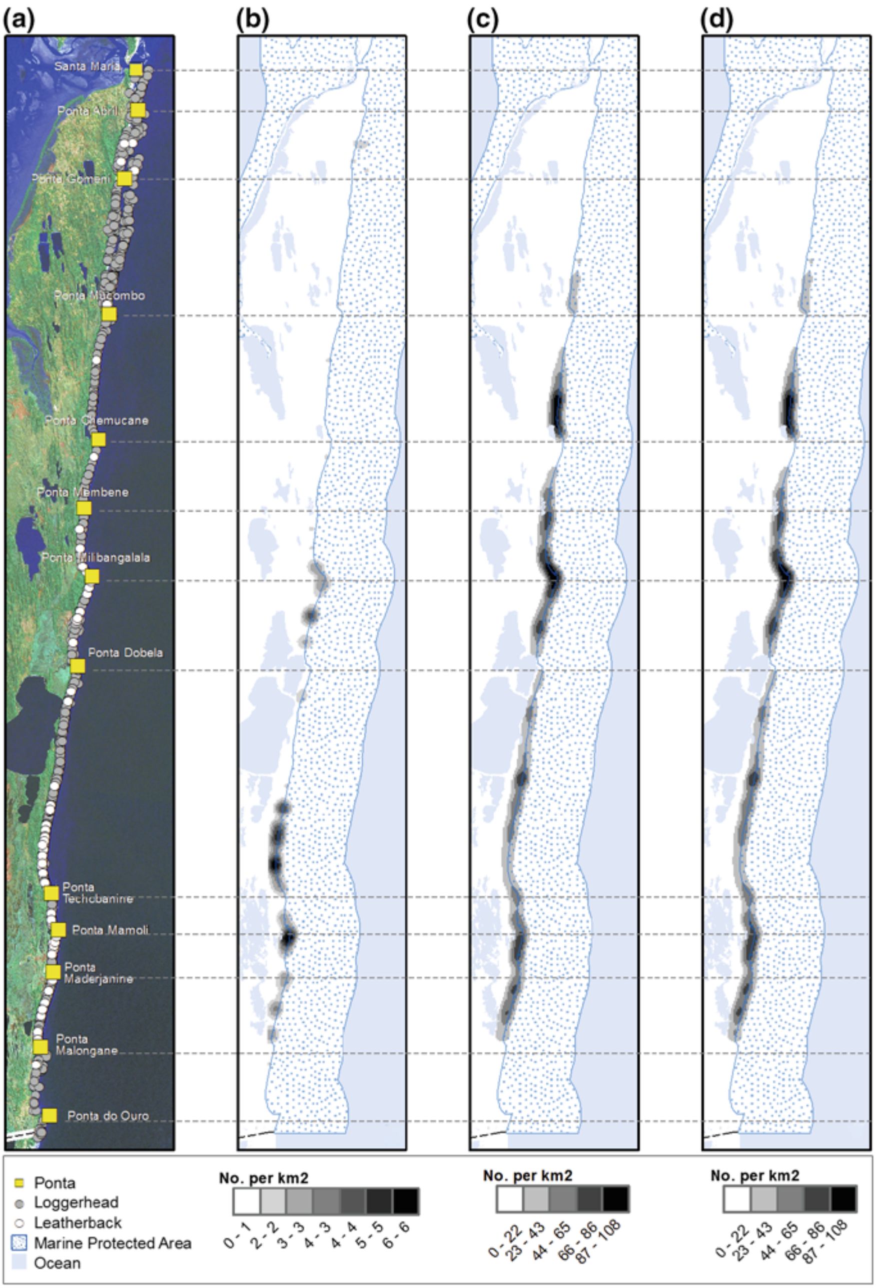

Fig. 17.5 **a** Turtle nesting sites in Ponta do Ouro Partial Marine Reserve, Mozambique. **b** Density of nesting sites for Leatherback Turtles. **c** Density of nesting sites for Loggerhead Turtles. **d** Density of nesting sites for both Leatherback and Loggerhead Turtles

Figure 17.5 clearly illustrates the value-added information which can be generated from point data through a full GIS to identify and prioritize interventions relating to turtle conservation. Monitoring of these sites prioritizes management interventions based on the indicators collected about these species.

17.4 Conclusion

Due to the vast landscape level planning which is being done by PPF in trans-frontier conservation, the need arose for a standardized methodology and process accompanied by widely distributed tools. The development of geoMEtri was therefore undertaken to address in-field and intra-agency management support, but also to allow for the exchange and distribution of data and information datasets. Offering these standardized tools to all stakeholders, proposing this means of data collection, information management, and knowledge-based results goes a long way toward informed decision support, among collaborators and importantly assists in alleviating misperceptions and conflicts which may exist between disparate parties in varying land use options.

In order to close the loop of this information flow, the employment of web-services feeds processed and value-added spatial information back to the contributors and users of the information. This has proven to inspire and motivate data contributors in that they are able to better understand and see their role which is being played in the bigger picture. The value and use of GIS has come a long way, and has become synonymous in the spatial planning domain. However, not all practitioners of various disciplines can manage and afford the time to become proficient and experts in the field of GIS analyses. A further advantage of this approach is that it exposes elements of the spatial technologies to all who are involved and who contribute to the planning, monitoring, and evaluation of TFCA-related work. GIS analyses is left then to the experts, however, with the advantage of showing and distributing data back to the contributors again highlighting the value of spatially processed and analyzed information offering important value-added decision knowledge.

As technologies merge toward a connected environment based around the use of smart devices, combined with crowdsourcing a very exciting future exists for leveraging data and information capture and the sharing of these results via effective reporting tools. It is with this in mind that PPF has engineered and will soon be launching geoMEtri for Google Android and Apple iOS mobile platforms.

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Chapter 18
The Technology Applicability Framework. A Participatory Tool to Validate Water, Sanitation, and Hygiene Technologies for Low-Income Urban Areas

André Olschewski and Vincent Casey

Abstract Decision-makers as well as practitioners in the water, sanitation, and hygiene (WASH) sector are facing serious challenges to keep existing WASH infrastructure in operation or to ensure provision of lasting and adequate WASH services. In many countries there are no tested procedures for assessing sustainability and scalability of new or existing technologies for providing adequate and lasting WASH services in a specific context. In the EU-FP7-funded project WASHTech, two tools for technology validation and introduction were developed and tested: the Technology Applicability Framework (TAF) and the Technology Introduction Process (TIP). The TAF is a comprehensive decision support tool centered around 18 sustainability indicators. In a participatory process it examines the financial, social, institutional, legal, environmental, technical, and capacity conditions in the given context from three perspectives: (i) users/buyers, (ii) producers/providers, and (iii) regulators/investors/facilitators involving all key stakeholders [e.g., municipality and nongovernmental organizations (NGOs)]. Consequently, the TAF determines the match—or mismatch—of the contextual conditions with the technology being considered and the key requirements for successful introduction. The TAF was field tested on 13 WASH technologies in three countries: Burkina Faso, Ghana, and Uganda. This paper presents the findings from the testing of the TAF and highlights potentials and limits of its applicability for assessing the sustainable application and scalability of WASH technologies. Relevant documents on the methodology, the testing as well as case studies and manuals are accessible in the public domain through www.washtechnologies.net.

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S. Hostettler et al. (eds.), *Technologies for Development*,
DOI 10.1007/978-3-319-16247-8_18

18.1 Introduction

Despite major efforts to increase water and sanitation coverage, many people living in urban and peri-urban contexts in developing countries still lack access to safe water and adequate sanitation (UNICEF 2014). One reason is that often introduced water and sanitation technologies are not sustainable in a given urban or peri-urban context. Even so-called 'appropriate' technologies often fail when the expectations of the users are not met and determining factors to sustain the technology are lacking (Cranfield University 2011).

Successful uptake and provision of lasting services are linked to many different aspects such as the acceptance of technologies, the ability of users to purchase the infrastructure and pay recurrent costs for operation and maintenance, the knowhow and skills to operate and maintain the system, and the resources and capacity of local governments to support user communities (Lockwood and Smits 2011). A technology can be considered successful when it is taken up by a great number of users (scaling up) and when it provides its services over a long time (sustainability) (Fig. 18.1).

Technology introduction and uptake are very complex and resource-intensive processes that involve many actors over a long period of time. Each introduction needs a careful, context-specific assessment of various sustainability aspects, and different market models ask for different roles for the actors involved (Heierli and Katz 2007).

A literature review on assessment frameworks for projects and technologies revealed the complexity of considering sustainability properly in assessment methodologies (Skat Foundation 2011). Most frameworks do focus on assessments of projects or programs with respect to sustainability; yet only some put technologies as the focus of the sustainability assessment, and none of them link the sustainability assessment with key issues around successful technology introduction.

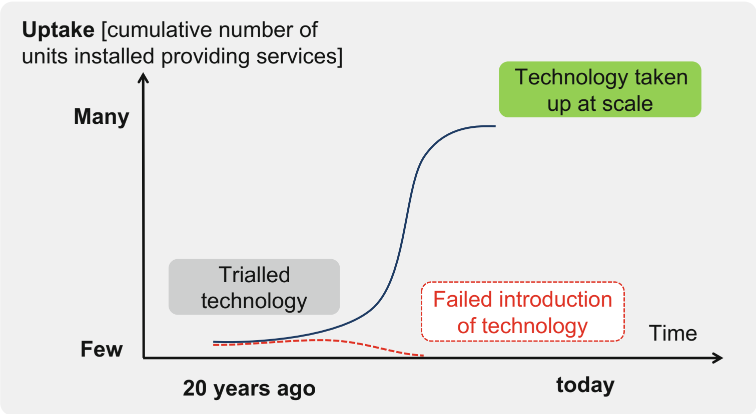


Fig. 18.1 Uptake dynamics for new technologies

Currently, more and more new technologies are being developed and promoted in the water, sanitation, and hygiene (WASH) market. Decision-makers are challenged with assessing the applicability and scalability and to make informed choices on promising technologies and service models that fit a specific context. The choice of the right, context-sound technology is a key requirement for achieving sustainable water and sanitation services (WaterAid 2011).

However, not all promising technologies that have been piloted and theoretically fulfill the requirements to be sustainable end up being scaled up. The reasons for this failure are manifold: for example, they may have not been considered by the national or local sector agencies as potential water and sanitation technologies, or proper maintenance may not be guaranteed due to a lack of skilled service providers.

For urban and peri-urban areas the situation is particularly challenging. Improving access in these areas might be highly sensitive to equity and inclusion issues, as improvements of services are often correlated with the level of wealth of the users (UNICEF 2012). In some areas where new piped systems were introduced, only the well-off benefited, as the poorer parts of the population could not afford these services or were not connected to the service at all (World Bank 2014). Hence, introduction of technologies providing services is very much linked to issues not only around equity, inclusion, and environment, but also accountability and governance.

Decision-makers such as governments, development partners, or private investors need efficient and robust tools for assessing the applicability of WASH technologies. However, so far there are no robust tested tools available which allow a comprehensive assessment of WASH technologies and which also evaluate the procedures around their introduction (Skat Foundation 2011).

The objectives of the WASHTech were therefore (i) to develop a comprehensive tool, the Technology Applicability Framework (TAF), to validate new or existing WASH technologies on their applicability within a specific context, and (ii) to develop a guide, the Technology Introduction Process (TIP) which supports decision-makers at the country, district, or city level in the successful introduction of a validated technology in a given institutional framework. The work was done in the framework of the EU-funded WASH Technologies project (WASHTech), which aimed to facilitate cost-effective investments in sustainable WASH technologies.

18.2 Design and Methods

18.2.1 General Overview

WASHTech was organized as an action research project to develop and test an assessment methodology with close involvement and interaction of partners in Burkina Faso, Ghana, and Uganda. As a starting point, key issues around WASH technologies and their uptake in the African continent were documented and discussed in a literature review (Cranfield University 2011). Additionally, a baseline study on knowledge, attitudes, and practice (KAP) of sector stakeholders toward WASH technologies and on existing processes for technology approval was carried out in the three African project countries of Burkina Faso, Ghana, and Uganda. It highlighted the different levels of practices, of formal procedures, and of attitudes around technology assessment (Cranfield University 2012). Changes in attitudes of key actors at the national level in these three countries were assessed throughout the project duration by collecting "change stories" and reviewing these using the "most significant change" methodology (Davies and Dart 2005). A strong embedding and communication strategy using learning alliances was designed and established to have full participation of the key sector stakeholders from the onset of the project.

In the WASHTech project the TAF methodology was developed and tested in three steps over a period of 3 years (Fig. 18.2).

In the first year, the activities focused on the definition of objectives and requirements for the tool, on the development of the draft TAF tool and of a methodology to test the usefulness of the TAF. Key requirements of the tool were defined by the project partners and the key actors in the WASH sector in the three countries. Inputs were collected through meetings at national levels and joint meetings and resulted in the following key points:

- the tool should be an assessment tool for the assessment of the applicability and scalability of existing and new WASH technologies;
- the tool should be simple to use;
- the target audience should focus on stakeholders from national and urban/ municipal governments, local private sector enterprises, local NGOs, research and development institutions, and also development partners and universities.

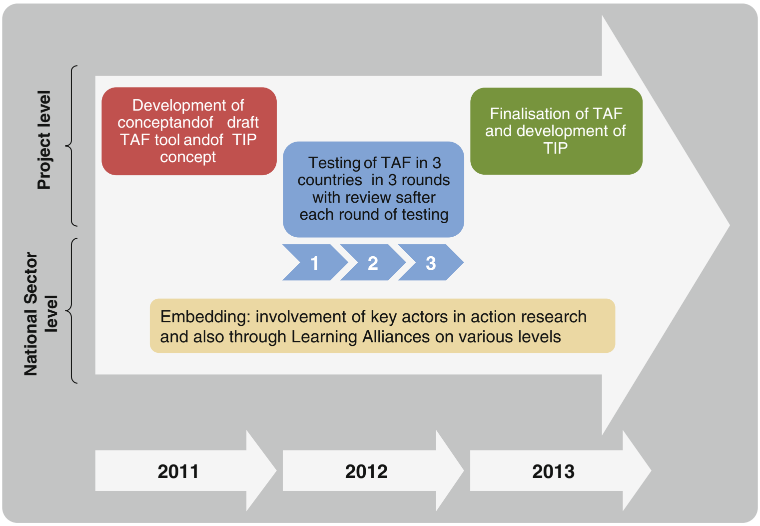


Fig. 18.2 Process of TAF development, testing, and embedding

Based on these inputs a draft methodology of the TAF and of the TIP was developed (Olschewski and Casey 2013). In parallel, the research methodology to test the usefulness of the TAF was developed (WaterAid 2012).

In 2012 the draft TAF tool was rigorously field tested in each of the three project countries. For the testing the TAF was applied to 13 different water, sanitation, and hygiene technologies, which were selected by the countries and which fit in rural, small town, and peri-urban contexts.

The selected technologies included:

- in Burkina Faso: Rope Pump, VIP Latrine, India Mark II, Urine Diversion Dry Toilet (UDDT), Sand Dam, and Water Harvesting Tank;
- in Ghana: Rope Pump, Pour Flush, Enviroloo, Slow Sand filter, Biofil toilet, Ghana-Modified India Mark II, and small piped systems using solar power;
- in Uganda: Rope Pump, UDDT, U2 Pump, Tippy Tap, small piped systems using solar power, and Ferro Cement Tank.

Although the WASH technologies tested with the TAF were situated in rural settings, the TAF is equally applicable for any urban WASH technology.

The field testing was organized in three rounds during which the testing was done in parallel steps in all three countries. Each round was followed by an extensive review of research findings with subsequent adaptation of the draft process and tools (Olschewski and Casey 2013). Testing the TAF in parallel steps allowed the teams to share experiences in review meetings at the end of each round of testing and to discuss and recommend amendments to the TAF. The amended TAF was then tested in the next round. After the final round of testing in 2013, a final version of the TAF was produced, including a short TAF manual which guides the user through the details of planning and application of the TAF.

18.2.2 Research Objectives and Structure for Research

The aim of the TAF testing research method was to evaluate the suitability and usefulness of the TAF for its intended users and intended purpose. To achieve this aim, the WASHTech consortium members agreed on a set of four research questions:

1. How easy do target users find the TAF to use?
2. How useful do target users find the TAF for an assessment of WASH technologies and the methods used to introduce them? Did the findings of the TAF square with people's perceptions of the technologies and approaches?
3. How should the TAF be adjusted to meet the needs of target users?
4. Will TAF users think differently about technologies and approaches after using the TAF?

For testing the TAF was applied at district and subdistrict levels, which means in real situations and workshops where all relevant stakeholders took part to ensure that the TAF reflected reality and could be applied in any rural or urban context. After each round of TAF application, study teams in each country sought the feedback and perspectives of different target users on the four questions and fed this into the further TAF design process.

In order to test the TAF, it was applied to WASH technologies and services at different stages of development, such as technologies considered to be "new," "promising," "successful," or "failed."

- "New" refers here to technologies that have not been tried in a given context but might have been tried in other contexts and are considered to offer opportunities worth investigating.
- "Promising" refers to technologies that are perceived to have yielded some useful experiences but have not yet achieved scale.
- "Successful" refers to technologies that have been tried and tested and are perceived to have achieved impact, scale, and sustainability.
- "Failed" refers to technologies that have been introduced and tried in some locations but have not yielded many successful experiences. "Failed" could mean that the technology itself, the introduction process, or both were not sufficient to produce promising results. However, "failed" does not mean that a technology might never be useful in a particular context.

For each of the 13 WASH technologies, two assessments of the performance of the technology were done by sector specialists: one prior to the TAF testing and one afterward. The purpose of asking about "perceived performance" before and after the TAF application was to gauge perceptions and performance of the technologies.

A combination of methods was used during testing to derive information about the TAF and the technologies being tested. These included focus group discussions, semi-structured key informant interviews, and literature reviews. The field visits enabled sufficient information about different technologies to be gathered. They captured the perspectives of users and local stakeholders and informed the TAF developers of the context in which the technology had been applied. The workshops enabled the outcomes of the field visits to be shared. At the workshops, the TAF was used to score the technologies being assessed in a participatory way and to discuss the findings.

There was not sufficient time and budget available to carry out a statistically significant number of household interviews to assess technologies. This reflects reality, as districts using the TAF would not have the time or budget available for such a survey. The TAF assessments are intended to be rapid, and the research method is likewise intended to reflect this reality.

The application of the TAF also enabled developing specific recommendation for these technologies to be used by the sector. These were published as technology briefs in separate reports.

18.3 Results

As a result of the action research approach and the testing of the TAF, two tools were developed: the TAF for assessing applicability and scalability of WASH technologies and the TIP, which is a generic guidance document to support the WASH sector in the introduction of promising technologies.

The TAF is a decision support tool that functions in three ways within a given context: (1) it identifies an applicable and sustainable WASH technology from those that are not; (2) it reveals risks and supportive factors that influence the successful introduction or roll out of this technology which need to be addressed prior to success; and (3) it triggers exchange and sharing between all key actors involved in the introduction of that technology in its context. Applying the TAF to new and also existing water and sanitation technologies should significantly increase the success of technologies and their introduction and, even more importantly, the sustainability of the water and sanitation service delivery for the urban poor. The target users of the TAF include national and urban/municipal governments, local private sector enterprises, NGOs, development partners, research and development institutions, and universities. The TAF can also be used to monitor current WASH technologies in urban settings to determine success or identify hindering factors toward sustainability.

The core elements of the TAF are:

- a set of **18 indicators for a comprehensive assessment** of the applicability of technologies, and of successful introduction, sustainable use, and operation of technologies providing lasting services;
- a **participatory process of application** of the TAF with involvement of all relevant actors including users of the technology, providers of the technology, and regulators and facilitators in all steps of the assessment, including scoring;
- a **graphical interface** that facilitates transparent presentation and interpretation of results for all actors involved.

18.3.1 Comprehensive Indicator Set on Sustainability and Introduction Issues

The successful introduction of technologies needs to comprehensively address key issues of sustainability, e.g., affordability of costs for users. The analysis of case studies on technology introduction also revealed the urgent need to consider in the assessment methodology the particular perspectives of the key actors involved, as all these actors should take on specific roles in the process of technology introduction. The indicator system of the TAF methodology therefore reflects the six

Perspective / Sustainability Dimension	User / buyer	Producer / provider	Regulator investor facilitator
Social	(1) Demand for the technology	(2) Need for promotion and market research	(3) Need for behavioural change and social marketing
Economic	(4) Affordability	(5) Profitability	(6) Supportive Financial Mechanisms
Environmental	(7) Potential for benefits or negative impacts for user	(8) Potential for local production of product or spares	(9) Potential for negative impacts or benefits for natural resources on a larger scale
Legal, institutional, organisational	(10) Legal structures for management of technology and accountability	(11) Legal regulation and requirements for registration of producers	(12) Alignment with national strategies and validation procedures
Skill and knowledge	(13) Skill set of user or operator to manage technology including O&M	(14) Level of technical and business skills needed	(15) Sector capacity for validation, introduction of technologies and follow up
Technological	(16) Reliability of technology and user satisfaction	(17) Viable supply chains for product, spares and services	(18) Support mechanisms for upscaling technology

Fig. 18.3 The 18 TAF indicators

sustainability dimensions with three perspectives of key actor groups: the user of the technology, the producer or provider (supply chain) and the regulator, and investor or facilitator of the introduction process. For each match of dimension and perspective, one key indicator was selected (Fig. 18.3).

For each of the 18 TAF indicators a specific questionnaire has been developed which includes 4–6 guiding questions and one scoring question. In the assessment workshop after the field visits, the answers to all questions were discussed within the scoring workshop participants, including the representatives of all three perspectives and additional participants. For the data validation and to go through all questions in a scoring workshop setting, usually a one-day workshop was organized. To allow participation of the user community in the workshop, the event was organized within the district of discussion. In their feedback on the TAF testing the actors involved acknowledged that all 18 indicators were needed to allow a comprehensive assessment.

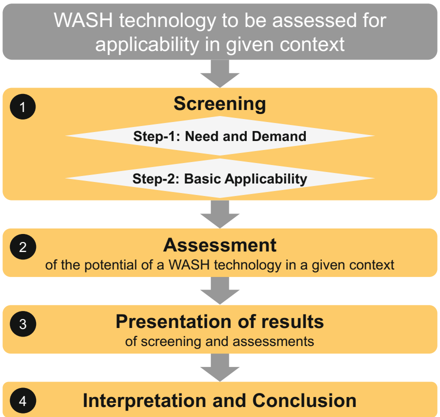
18.3.2 *Clear and Participatory Process to Give Everybody a Voice*

Technology introduction needs substantial investment of financial resources, e.g., to do market research, product development, and testing, as well as to launch it to the wider market. However, vested interests could influence the process and results of technology assessments. In urban and peri-urban areas these risks are also prominent, as dynamics and driving forces such as from the local private sector or vested interests of key actors such as leaders might be very strong. Decision-making processes for technology introduction are often not transparent in terms of process and communication so that less influential parts of the population have no voice, such as the poorest of the urban population.

The TAF is applied to one technology in one specific context, e.g., technology X in district YZ, and is carried out in four steps (Fig. 18.4). The TAF methodology follows a stepwise transparent process with defined tools and a transparent and participatory process for assessing WASH technologies. In the field visits and in the scoring workshop all relevant stakeholders do participate and have the opportunity for their voice to be heard.

In the first TAF step, the screening, WASH technologies are identified that are found to be unsuitable in meeting users' needs within the specified context. During the step 2, the TAF users undertake a comprehensive assessment of the applicability and scalability of the technology in a specific context using 18 indicators. Both quantitative and qualitative data are gathered from national, local, and community levels and from various other stakeholders using also field visits. Data and information undergo a process of validation in a workshop involving all relevant stakeholders. In the scoring workshop each indicator is designated a score/symbol discussed and agreed upon by consensus of the workshop participants. The scoring bears resemblance to a traffic light

Fig. 18.4 Flow of the 4 TAF steps



system. In step 3 the results of the screening and assessment on the applicability of a technology within a given low-income urban context will be visualized. This forms the basis for the interpretation of the results in the step 4.

In their feedback from the TAF testing the actors involved stressed that they see a clear need to have a well-structured process as basis for an assessment using the four steps. In particular, it was highly appreciated that the TAF foresees the involvement of all key people in key steps of the assessment process such as the users and the regulator.

18.3.3 The TAF Profile Allows Visualization of Results and Offers Transparent Options for Interpretation

Based on the results of the scoring workshop the scores for all 18 indicators given during the assessment (step 2) are presented in a graphic profile following the logic in the matrix (Fig. 18.5).

In this form of presentation, all six dimensions and perspectives are implicitly considered with the same weight. Indicators are not aggregated, e.g., per color or dimension, to keep the detailed information behind each score. This presentation also allows different entry points for interpretation such as per sustainability dimension, per perspective, or for specific topics or as an entire profile. In this form all 18 indicators have the same weight; however, for sensitivity analysis weighting factors can be introduced easily. Visualizing the results in this form allows all target users, including the users of the technology, who often have no technical

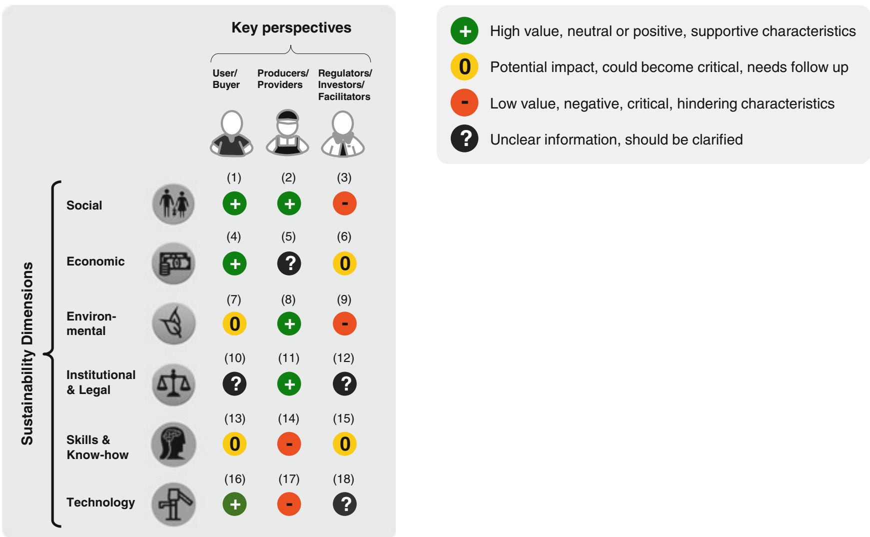


Fig. 18.5 Hypothetical example of TAF profile including scoring rules

background, to better understand the results and arrive at a more transparent and higher level of understanding of sector issues. This presentation fosters transparency of the results and maybe even acceptance of the results. Based on a higher acceptance there is a higher chance to develop and agree upon appropriate introduction mechanisms for adoption and/or scaling up and mobilize support in moving forward with the results of the technology assessed.

The results of the TAF application, including the screening and assessment, are documented in a short report highlighting the context-specific potential concerning applicability of a technology being considered for introduction in a specific context at a city/town or community level. The TAF report also indicates which topics need further attention for the technology to be successful from a sustainability perspective. For example, with areas of risk defined (red button with negative symbol), discussions on developing mitigation measures are better structured. However, the TAF results may also be negative for a technology, that is, the considered technology should not be applied in this context for reasons listed. In combination, the report and the process of the TAF application provide a robust basis for decision-making regarding a technology in an urban or peri-urban context; however, the TAF is not a selection tool that indicates which technology fits best.

In their feedback from the TAF testing, the actors involved liked the graphical way of presentation. There was no need expressed for changing the scoring rules. It was recommended to enrich the scores with verbal explanation and secondary information that is relevant. However, it was stressed that strong speakers could influence the discussion and the scoring. There are limits on how far a participatory approach can deal with these risks. In the TAF manual some concrete suggestions are included for how to deal with this situation. In any case when applying the TAF, a strong and independent facilitator is needed to steer and guide the process.

Actors involved in the field testing of the TAF also raised the issue of the costs for applying the TAF, as it involves field visits to the districts and workshops with participation of different partners from local and regional levels. Based on the experiences from the TAF applications, the costs for applying the TAF are about US$2000 for one assessment of one technology in one region, assuming that the facilitator is already familiar with the TAF methodology. As the methodology is based on field visits and workshops, there is not much space to reduce the costs because many costs, such as for local transport or for workshops, are fixed costs. However, compared to the lost costs that are often experienced in many poorly designed or managed technology introductions, the costs of applying the TAF seem to be rather low. A detailed description on preparatory steps needed when applying the TAF, e.g., identification of the cost figures for operation and maintenance as well as the cost drivers for applying the TAF, are documented in the TAF manual (Olschewski 2013). The TAF manual, technology briefs, and all other document reports on TAF and TIP are in the public domain and available through www.washtechnologies.net.

In all three countries host organizations at the national level were appointed by the leading ministries to host and streamline the TAF and TIP beyond the WASHTech project. The country hosts were the Community Water and Sanitation

Agency and Environmental Health and Sanitation Directorate (MoLGRD) in Ghana, the Appropriate Technology Centre of the MoWE in Uganda, and the Direction d'Etudes et Information sur l'Eau (DEIE) in the newly established Ministry for Water and Sanitation in Burkina Faso. In each of the three project countries, WASHTech also triggered a participatory process for defining and agreeing upon tasks among the various key actors involved in technology introduction based on the TIP. The resulting guidelines were embedded in core sector documents for technology validation at the national level. The TAF was also applied on WASH technologies in countries outside the WASHTech project such as in Tanzania, Afghanistan, South Sudan, and Nicaragua. In Nicaragua, the TAF was applied using the documents available without any further external training or remote support. The TAF users were very satisfied with the process, and results and more applications of the TAF are planned.

Also, in the existing WASHTech partner countries the TAF was further applied in 2014. Recently in Ghana, the Biofil toilet was validated and approved officially by using the TAF methodology. These tests have been initiated without external funding.

18.4 Conclusions

The experiences from the TAF development and testing in various countries and contexts highlighted the importance of allowing for exchange between different actors and participatory approaches when discussing applicability of WASH technologies and the way of introduction. This is also true in urban and peri-urban contexts which offer high potential for dynamics and interferences.

The concept of joint workshops allows bringing in each voice and thus strengthening accountability and governance. It helps to develop a common understanding of issues in the WASH sector, to develop mitigation measures, and to foster more structured sharing and, thus, innovation.

The uptake of the TAF methodology in all partner countries as well as beyond shows that there is a clear need for such tools and that the TAF has the potential to provide the support needed. In combination, the TIP and the TAF can be used as a tool box to support the testing and approval of WASH technologies; however, the results can also be used to support the design of introduction processes and to monitor technologies. More TAF applications are planned in the WASHTech countries as well as elsewhere.

So far the TAF has been designed for assessments of WASH technologies, however, due to its flexible and comprehensive approach it was already modified to allow assessment of WASH approaches such as assessing self-supply and even other technical solutions such as those for housing projects in the Philippines.

In order to extend the scope of TAF, i.e., toward approaches but also to improve its cost effectiveness, more research is needed. Additionally, long-term follow-up should be established to document the impacts of the use of the tools on the performance and level of innovation in all countries that use the tools.

Acknowledgments WASHTech was a 3-year action research project funded under the EU FP7 framework and implemented in the period 2011–2013. WASHTech involved all relevant stakeholders at national level in all three African partner countries Burkina Faso, Ghana, and Uganda throughout the project period to ensure strong embedding and realistic results.

The consortium partners included IRC International Water and Sanitation Centre, Cranfield University, Skat Foundation, WaterAid (in the United Kingdom and in all partner countries), WSA in Burkina Faso, TREND and KNUST in Ghana, and NETWAS Uganda. We are grateful to all partner organizations that have been involved in the testing of the tool and contributed to the improvement of the tools and their embedding at national and international levels. Particularly, we want to thank Kerstin Danert and Sean Furey for their inspiring inputs and motivating support and Stefan Diener for his great support in reviewing this paper.

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Chapter 19
Lessons from the Evaluation of a Clinical Decision Support Tool for Cardiovascular Disease Risk Management in Rural India

Arvind Raghu, Devarsetty Praveen, David Peiris, Lionel Tarassenko and Gari Clifford

Abstract The rise of chronic disease and failure in the implementation of adequate prevention strategies places a heavy burden on the health systems of low- and middle-income countries. Despite vast interest in mobile health (mHealth) technologies, there is a lack of evidence for the clinical impact and scalability of mHealth tools for managing chronic diseases in a resource-constrained setting. This paper outlines the development and field evaluation of an mHealth solution in the form of a clinical decision support (CDS) tool. The CDS tool was tailored for use by healthcare providers within a primary care setup in rural India to perform screening and management of cardiovascular disease (CVD) risk. The CDS tool was designed prior to, and during an agile development phase that comprehensively engaged end-users namely primary health centre (PHC) physicians and rural non-physician healthcare workers (NPHWs). Lessons learnt from a pilot implementation are presented to help inform strategies for large-scale evaluation of mHealth technology in resource-constrained settings.

19.1 Introduction and Purpose

Cardiovascular disease (CVD) is an established cause of mortality and morbidity worldwide especially in low- and middle-income Countries (LMIC) (Stewart and Sliwa 2009) and has accounted for over 80 % of all CVD-related deaths in the past (WHO 2011). Current preventative measures are inadequate and recent

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S. Hostettler et al. (eds.), *Technologies for Development*,
DOI 10.1007/978-3-319-16247-8_19

epidemiological and demographic transitions in LMICs have contributed to increasing burden on already constrained health systems that have not innovated on the traditional, physician-centric system equipped to treat acute care conditions. To manage the epidemic of CVD in resource-constrained settings, Mendis (2007) describes the need for both population-based strategies, and strategies specific to high-risk groups, in order to shift the distribution of chronic disease risk factors toward the healthier side (Mendis 2007). The author also reflects on necessary investment in training of healthcare workers and adoption of an absolute risk approach in managing CVD. The consensus in literature on global CVD prevention has been to look toward innovative, integrated management approaches that can offer evidence for preventive strategies (Beaglehole et al. 2008). However, there is little evidence on established, scalable, and sustainable solutions for large-scale CVD risk management in LMICs.

The number of mobile subscriptions in the world is now equivalent to the global population and mobile penetration rates in developing countries are on average 89 % and continuing to rise (ITU 2013). In developing markets, smartphones have been available for purchase without a contract less than US$100 and the costs are expected to drop. Contract-free Android devices are now available for US$50 or less (Bloomberg Technology 2013). These are favorable factors which contribute to the promise of the expansion of mobile health (mHealth), a field that evoked considerable interest in recent times as a means of delivering essential healthcare services.

Qiang et al. (2011) from the World Bank reviewed over 500 mHealth projects in developing countries, focusing on case studies from India, Kenya, and Haiti (Qiang et al. 2011). They state that although a large number of mHealth pilots have been carried out, few have been designed to scale and very little are able to scale to national programs. The authors also highlighted the challenges in delivering mHealth solutions to rural areas which are limited in infrastructure and skilled workforce. The most common mHealth interventions reported in the literature involved text messaging and phone call reminders to encourage healthy behavior, attendance at follow-up appointments, and healthcare data collection (Källander et al. 2013). However, after the completion of these initiatives, there is little evidence of adoption, best strategies for engagement, efficacy, and effectiveness (Tomlinson et al. 2013). In fact, to-date, there are few mHealth studies that have demonstrated an impact on clinical outcomes in LMICs (Källander et al. 2013).

This paper discusses the design and development of a mHealth clinical decision support (CDS) tool for managing the risk of CVD in rural India as well as the lessons learnt from pilot testing. This evaluation was performed as part of the SMART-health India (Systematic Medical Appraisal, Referral and Treatment-health) program headed by The George Institute for Global Health and Oxford Institute of Biomedical Engineering which aims to develop novel technologies, such as electronic decision support systems, to improve the quality of healthcare in resource-constrained settings.

19.2 Design and Methods

19.2.1 CVD Risk Algorithm: Implementation and Validation

A single CVD screening and management algorithm was developed based on a synthesis of recommendations from Indian and International CVD screening and management guidelines (Indian National Programme for Prevention and Control of Diabetes 2014; American Diabetes Association 2011). The World Health Organization/International Society for Hypertension (WHO/ISH) risk charts were used for assessment of 10-year risk of a fatal or nonfatal cardiovascular event (myocardial infarction or stroke) (WHO/ISH 2011). Figure 19.1 illustrates a color-coded chart to predict the risk of CVD based on multiple risk factors, including age, smoking status, gender, level of blood cholesterol, blood pressure, and absence or presence of diabetes. There are different risk charts based on information on the absence or presence of diabetes. Also, depending on the usage of cholesterol information, low or high information charts are provided [High information charts (HIT) are used when blood cholesterol information are available, whereas Low information charts (LIT) do not use cholesterol information for predicting risk]. These charts have been designed primarily for LMICs and are tailored to 14 WHO epidemiological

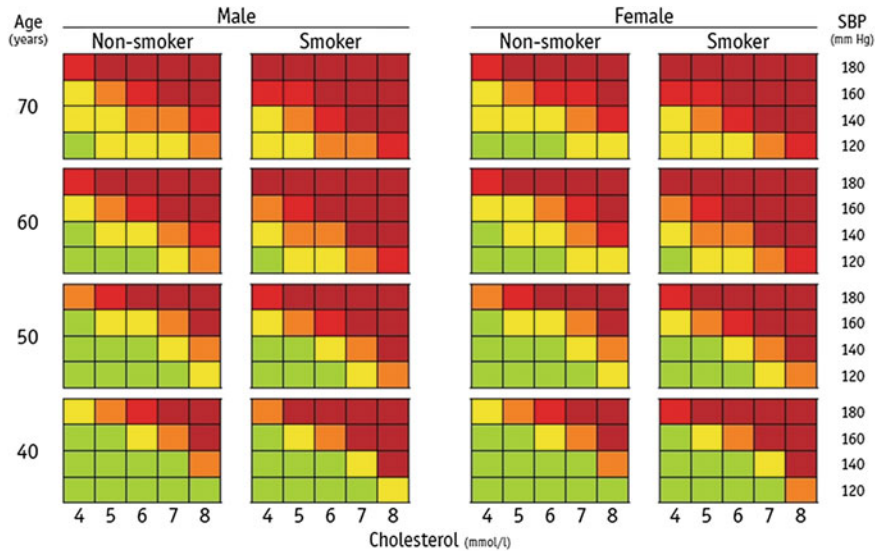

Fig. 19.1 WHO/ISH CVD risk prediction chart for individuals who do not have diabetes. The 10-year CVD risk is stratified into five risk ranges and color coded as follows: Low (less than 10 %) risk is indicated by *green squares*. *Yellow* indicates 10 % to <20 % risk*; orange* indicates 20 % to <30 % risk; *red* indicates 30 % to < 40 % risk, and *maroon* represented the highest level of risk (greater than 40 %)

subregions, including South-East Asian Region-D (SEAR-D), which can be used by all South-East Asian countries except Indonesia, Sri Lanka, and Thailand.

The screening and management algorithm was validated in two stages. The first stage for validating the software involved a physician and engineer who independently implemented the algorithm using two different software packages, namely SPSS (IBM, New York, USA) and the other in Java as an Android application. The two implementations were tested using data from the Andhra Pradesh Rural Health Initiative (Joshi et al. 2012) and code was rechecked whenever there were disagreements between the two sets of output variables. This process was repeated until 100 % agreement between the outputs was reached. The second stage involved a comparative review of the algorithm's output from the Android application with the existing guidelines. This was performed by a physician not involved in the algorithm development. This resulted in minor changes being made to the algorithm, which was subsequently reimplemented in SPSS and Java (as an Android application) and rechecked to achieve 100 % agreement between the outputs.

19.2.2 Adapting the mHealth CDS Tool for End-Users in a Resource-Constrained Region

The CDS tool design was performed in two stages following an agile development methodology. This followed user centered design (UCD) where the philosophy is to iteratively involve the end user [in our case, rural non-physician healthcare workers (NPHWs) and primary health centre (PHC) physicians], improve prototype versions based on eliciting feedback, and employing formal usability testing techniques. However, unlike UCD employed in customer-oriented products, our "customers" (the PHC physicians and rural NPHWs) cannot drive the tool design primarily because of relative unfamiliarity with technology and lack of sufficient background knowledge (such as for instance on CVD for NPHWs). Therefore, we employed an observer team including clinicians, an engineer, and sociologists to systematically identify and evaluate user needs. This led to gradual refinement of the tool's user interface and incorporation of appropriate features with proper engagement of the PHC physicians, NPHWs, and randomly selected members of the local community who were not medically trained. The end stage client-side application was designed to run on Android devices (running version 4.1 and above) with a process flow that was broken down into four steps: (i) Patient registration, (ii) assessment of medical history, (iii) measurement of risk factors (including blood pressure, blood glucose), and (iv) 10-year CVD risk prediction and CDS on CVD management.

Integration with open-source tools. In order to increase interoperability and scalability as well as to lower implementation costs, our CDS-based CVD risk tool was integrated with established open-source telemedicine frameworks namely Sanamobile and OpenMRS. Sanamobile (Celi et al. 2009), is an open-source Android-based mobile health platform that was designed for use by healthcare workers in LMICs, and is supported by a global community of programmers. Sanamobile has been applied in a variety of settings from cardiovascular health monitoring in South Africa and China (Arteta et al. 2012) to diabetic foot ulcer management in Greece (Dafoulas et al. 2012). Sanamobile is designed to work with any medical record system, but is primarily supported for use with OpenMRS, which is an open-source, community-driven electronic medical record (EMR) system and has been widely implemented in Africa notably for managing HIV (Wolfe et al. 2006; Clifford et al. 2008).

To retain the user interface and features developed through our UCD process as well as utilize the Sanamobile system, we developed an interprocess communication (IPC) framework to allow exchange of data and initiation of client-side services such as background uploading to the server. This was achieved by using the Android Interface Definition Language (AIDL) (2013). The library code created can act as an interface for any third-party application to use Sanamobile's client-side data management system and its middle-ware Mobile Dispatch Server (MDS) to upload data on to the EMR. A short text messaging (SMS) module was also redesigned for the OpenMRS system that allowed for one-way communication to both PHC physicians and NPHWs through text messages.

19.2.3 Field Evaluation

The resultant mHealth system we created was deployed across 11 villages in southern India for screening and management of CVD by 3 PHC physicians and 11 NPHWs. The infrastructure for data collection and exchange is illustrated in Fig. 19.2 and can be thought of as a four-step process as follows. Door-to-door data collection (*Step 1*) of an individual is performed for assessment of CVD risk using the CDS tool. Point-of-care decision support (*Step 2*) and appropriate management guidelines including referral to a doctor is available if the patient is at high risk of developing CVD in the next 10 years (according to the prediction model built into the app). Uploading of all the collected data to the EMR (*Step 3*) was performed using Sanamobile's client-side application to the server-side MDS which pushes data subsequently to OpenMRS. Treatment and follow up (*Step 4*) were performed by the physician when the high-risk patient visited their clinic. The physician also uses the CVD tool as a stand-alone decision support system to screen and treat patients who visit his or her clinic.

The Android application was designed to support the local language (Telugu) and optimized to run on a high-end version of a low-cost tablet (£100) for use by NPHWs, and a Samsung Galaxy 7-inch tablet (£160) to be used by PHC physicians. Blood pressure was measured and transmitted via Bluetooth to the tablet-based CDS using a validated blood pressure device (Westhoff et al. 2007). Blood glucose was measured using LifeScan's OneTouch Ultra2 glucometer. Although the Sanamobile system offers techniques such as packetization for data uploads during periods of limited internet connectivity, the CDS tool was built with network

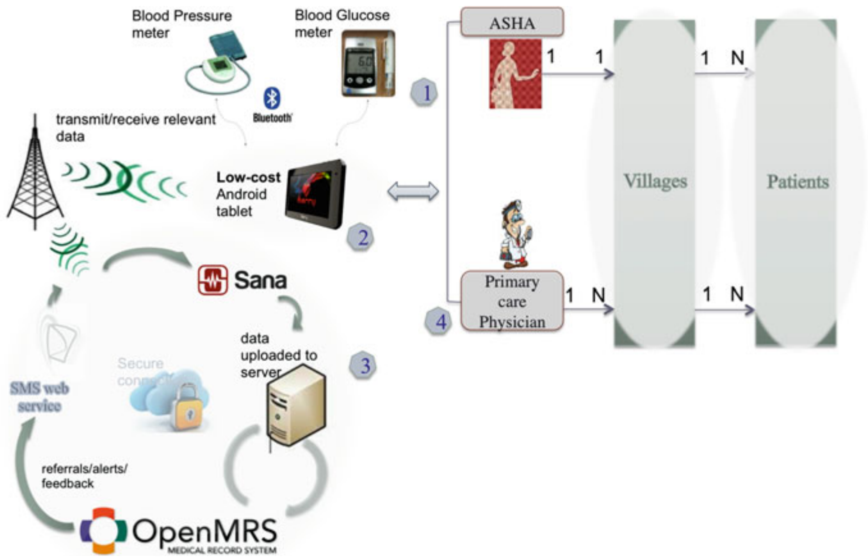

Fig. 19.2 Pilot implementation of the CDS tool explained in four steps. *Step 1* A NPHW (such as an ASHA or Accredited Social Health Activist, who plays an important role in acting as an interface between the public health system and villages) visited localities in her village to screen individuals above 40 years of age for their CVD risk using the CDS tool. *Step 2* After collection of demographics, medical history, and risk factors, the CDS tool provides point-of-care decision support based on the individual's risk of CVD as well as appropriate management recommendations including lifestyle advice and referral to the doctor if deemed high risk. *Step 3* Patient information is uploaded on to the server-side electronic medical record system OpenMRS via Sanamobile. *Step 4* Patient visits a PHC physician for treatment guidance and follow-up schedule.

testing tools to indicate the best available connection and continuously inform the level of connectivity in different villages involved in the pilot study.

The CDS tool was pilot tested to determine feasibility and acceptability within the context of a rural primary care setting in India through a mixed-methods approach. Quantitative evaluation of the CDS tool was performed via a questionnaire that users were presented with at the end of each CVD risk assessment procedure. Qualitative interviews were also conducted with NPHWs, PHC physicians, and individuals who were screened for CVD risk.

19.3 Results

PHC physicians and NPHWs screened a total of 292 consenting individuals (median age 52.5 years, IQR 20 years). In over 72 % of the participants screened, the end-users agreed the CDS tool was easy to use. No user gave the tool a rating below 3 on a scale of 4, with 4 being most user-friendly and 1 being the least.

Qualitative findings indicated that all users found the CDS tool useful and felt it enhanced their capacity as a healthcare worker. Both NPHWs and PHC physicians also found the tool easy to adapt into their workflow. Technical barriers specific to the use of CDS tools in resource-constrained settings were identified. Some of the lessons learnt from the design and pilot implementation of the CVD risk tool in rural India are presented below.

19.3.1 General User Acceptance of the CDS Tool

Qualitative findings indicated that all NPHWs found the CDS tool useful and felt that not only did it enhance their capacity as health workers, but also helped in raising patient awareness of CVD and healthy behavior.

> I like all the features of the tool. I feel it will be very useful to the community by creating awareness about their health and to take care of it. This tool is giving an opportunity to them to learn about their health. (NPHW 6, age 29)
> They (patients screened) all felt happy to know their CVD risk in advance and to learn about the impending risk of those diseases. They also informed that by knowing about these things, what care needs to be taken is made clear to them. They are all happy about the utility of this tablet and the screening procedure (NPHW 2, age 29)

The CDS tool also benefitted the NPHWs over conventional paper-based data collection methods. The use of the Bluetooth blood pressure device, and glucometers accelerated the process of collecting risk factor measurements.

> If paper based, it would take a lot of time, it may take nearly half an hour to record everything But in TAB, it takes some time at the registration page but takes no time to measure BP, sugar etc., if we do it quickly, it would end fast. (NPHW 9, age 31)

19.3.2 Adoption of Technology

During the UCD phase, different ways of communicating the meaning of absolute CVD risk developed over time (such as through graphs) was tested on participants from different villages. The final design of the CDS-based CVD risk tool used a risk projection "meter" using a needle and dial, similar to a speedometer, with the risk ranging from 0 to 100 %, with the addition of color coding which mapped to the WHO/ISH charts. The NPHWs found this useful to explain the relation between different risk factors such as BP and absolute risk.

> We show them (patients) the risk meter. When age is moved, this bar moves along. When the age or BP is high this increases so, we are showing this… This is easier to understand, as this will move from here to here, whereas that doesn't move, so this is easier to understand and also to show the difference comparing with the age and BP (NPHW 10, age 30)
> I used to show them (patients) this (risk meter) and let them know about the BP… Simply explaining will not work. If we show this page they can understand it well. If we show them what is risk, what is normal reading, they understand it well (NPHW 9, age 31)

The NPHWs experienced difficultly in operating the Bluetooth BP device initially, and some preferred manual entry or sought assistance. Toward the later stages of the pilot study (which was spread over 4 weeks), they reported less difficulty and expressed a preference for Bluetooth transmission to collect the BP data.

> In the beginning I could not have the reading afterwards, it is ok… First, it was difficult and now it is easy to transfer. If I press the button, it will take the reading (NPHW 9, age 31) Yes sir, once I felt difficulty in the beginning and then I called sir over phone and asked for the guidance… Initially I thought typing BP values are easy… I felt somewhat difficulty (to send BP data wirelessly) in the beginning… afterwards, I could do it… (NPHW 11, age 35)

19.3.3 Barriers to Increased Adoption

Use of pictograms was recommended by the NPHWs to make a greater impact when communicating lifestyle modifications such as salt reduction and physical activity to local members of the community.

> That will still be better and if we show the spoon in a salt bowel or pictures of exercise and… if we show the pictures it will be better… and they will be seen and hence it is easy; to explain also… and they understand by seeing… (NPHW 4, age 32)

Although members of the community valued the role of the CVD risk projection dial in understanding the relation between different risk factors and absolute CVD risk, they did not perceive the meaning of absolute risk in itself. This indicated the need for better mechanisms of conveying absolute risks, such as through colored bars and the need to minimize patient exposure to their percentage of CVD risk.

> They (patients) don't understand the percentages… I would tell them that as you have high risk you have to go to the doctor, or if the risk is too low then would say you won't need a doctor as your risk is very low. Some of them are asking and some of them are not asking such questions on what is this percentage. I suggest without using the words percentage we can convey them this in degrees like more, less and normal or too high (NPHW 10, age 30)

The low-cost Android tablets used by the NPHWs encountered difficulties including the uptake of power when connected to a mains power supply. This was compounded by the limited availability of electricity throughout the day in rural India.

> Charging is a main issue for me. My tablet was not getting charged though I have been putting it on charge for a long time (NPHW 6, age 29)

During the training phase of the study, the introduction of automated text messages from the EMR found poor acceptability among community participants. This was because most eligible participants did not read text messages (which was in English, adding to the language barrier), and furthermore were used to receiving a lot of spam texts. The SMS feature was therefore not feasible and was dropped.

Patient data upload to online EMR. Just under 50 % out of the total CVD risk assessments performed were available in the online medical record at the end of the pilot study. On further investigation from client and server log files, it was observed that there were frequent fluctuations in the signal strength and type of signal (such as EDGE or HSDPA) in the villages that resulted in stalled uploads. In addition to this, it was found that when the low-cost tablet had a battery power level less than 10 % (which was observed to be a relatively frequent occurrence), the network adapter automatically switched off. Certain practical issues were also observed; for instance, upon finishing a risk assessment, the NPHW usually locked the tablet in a bag, compounding the problem of weak reception.

19.4 Conclusion

The focus of this study has been on the design, development, and pilot testing of a mobile-based CDS tool for the assessment and management of CVD risk for a rural Indian population. It was found that to maximize adoption, enhance capacity building, and achieve full utility in resource-constrained settings, mHealth tools need to be iteratively designed with the end-users, including local communities and healthcare providers, factoring both the local technical and social considerations. This study was a cross-disciplinary effort that brought together clinicians, epidemiologists, and engineers across four continents to develop solutions and understand preliminary effectiveness, feasibility, and acceptability of the CDS tool which was tailored to the population through our UCD phases. The use of open-source rather than proprietary software in our mobile-based CDS tool is believed to offer increased scalability, lower cost, and increase collaboration efforts for low-cost health technology which could be reused in similar settings. The findings of the pilot study indicate that a mobile-based CDS tool can contribute to improved CVD detection and management in the Indian primary health system. Lessons from our pilot implementation shall inform further refinement and enhancement of the CDS tool. For instance, more robust software will be used to deal with connectivity changes (or to find the most stable connection type) and tablets will be tested for network issues prior to selection in order to minimize data loss on the server. New features such as voice messages will be included to replace the existing SMS module. The updated mHealth system will be evaluated in a cluster randomized controlled trial involving 54 villages and over 16,000 high-risk individuals from villages in southern India.

Acknowledgments This project was funded by the National Health and Medical Research Council (NHMRC), Australia, under the Global Alliances for Chronic Disease Grant (ID1040147). Arvind Raghu is funded by the Wellcome Trust/EPSRC Oxford Centre for Excellence in Medical Engineering (grant number WT 088877/Z/09/Z), University of Oxford. Devarsetty Praveen is supported by the Australian Agency for International Development (AusAID). David Peiris is supported by a NHMRC post-doctoral fellowship (ID 1054754). The authors wish to thank the support of the Sanamobile development team, especially its lead software developer Eric Winkler.

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Chapter 20
Comparing Cookstove Usage Measured with Sensors Versus Cell Phone-Based Surveys in Darfur, Sudan

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Abstract Three billion people rely on combustion of biomass to cook their food, and the resulting air pollution kills 4 million people annually. Replacing inefficient traditional stoves with "improved cookstoves" may help reduce the dangers of cooking. Therefore analysts, policy makers, and practitioners are eager to quantify adoption of improved cookstoves. In this study, we use 170 instrumented cookstoves as well as cellphone-based surveys to measure the adoption of free-of-charge Berkeley-Darfur Stoves (BDSs) in Darfur, Sudan where roughly 34,000 BDS have been disseminated. We estimate that at least 71 % of participants use the stove more than 10 % of days that the sensor was installed on the cookstove. Compared to sensor-measured data, surveyed participants overestimate adoption both in terms of daily hours of cooking and daily cooking events ($p < 0.001$). Average participants overreport daily cooking hours by 1.2 h and daily cooking events by 1.3 events. These overestimations are roughly double sensor-measured values. Data reported by participants may be erroneous due to difficulty in recollection, courtesy bias, or the desire to keep personal information obscure. A significant portion of sensors was lost during this study, presumably due to thermal damage from the unexpected commonality of charcoal fires in the BDS; thus pointing to a potential need to redesign the stove to accommodate users' desire to cook using multiple fuel types. The cooking event detection algorithm seems to perform well in terms of face validity, but a database of cooking logs or witnessed accounts of cooking is absent;

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S. Hostettler et al. (eds.), *Technologies for Development*,
DOI 10.1007/978-3-319-16247-8_20

the algorithm should be trained against expert-labeled data for the local cooking context to further refine its performance.

20.1 Introduction and Purpose

Worldwide, 3 billion people rely on combustion of biomass to cook their food (World Bank 2011). Resulting indoor and outdoor air pollution kills 4 million people every year, making cooking smoke one of the world's greatest environmental health problems (Lim et al. 2013). Many efforts to reduce the dangers of cooking smoke focus on replacing inefficient, high-emission, traditional stoves with "improved cookstoves," yet widespread and sustained adoption remains elusive, and impacts are poorly understood.

Analysts, policy makers, and practitioners are eager to know which cookstoves and marketing approaches can increase user-acceptance and long-term adoption. Evidence remains limited in part because it has been difficult to collect accurate and ample data on cookstove use. Because intensive direct observation can be expensive, onerous, and alter user behavior (Landsberger 1958); most studies of cookstove adoption rely on infrequent survey-based self-reported data (Lewis and Pattanayak 2012; Burwen 2011). These data are subject to two types of error: First, respondents may overreport normative behaviors, generating "social desirability" or "courtesy" bias (Edwards 1957; Nunnally 1978). Overreporting use leads to systematic overestimates of adoption, which leads to systematic downward bias on estimates of any positive impacts of adoption. Even without intentional misreporting, respondents can struggle to recall and aggregate over large periods, but more frequent visits are prohibitively expensive at scale and onerous for participants. Even if recalled information is unbiased on average, any measurement error in the dependent variables (say, fuel expenditures) reduces the precision of estimates leading to reduced statistical significance (Das et al. 2012).

Given these challenges and needs, the ability to monitor cookstoves' use with objective and unobtrusive means is critical to improving products, process quality, and properly measuring impact. Some studies have begun to implement time-and-temperature logging stove use monitors (SUMs) which can measure cooking events without input from the user (Berkeley Air Monitoring Group 2013; Burwen and Levine 2012; Ruiz-Mercado et al. 2011, 2013; Thomas et al. 2013). Partnering sensors with traditional surveys allows estimates of the magnitude of error in self-reported usage. In Guatemala, Ruiz-Mercado et al. (2013) instrumented improved cookstoves with SUMs in 80 households every other month for 32 months. They find high usage (around 90 %) and relative consistency between survey and sensor-generated data. The Berkeley Air Monitoring Group (2013) found similarly accurate self-reported data for 25 cookstove users in Kenya. In Rwanda, Thomas et al. (2013) installed 27 SUMs on cookstoves and rotated them through 97 households for an average of 9.8 days each, staggered over 5 months. They find

SUMs-measured usage (73 % of users adopt) to be significantly lower than self-reported data (90 %).

Primary weaknesses in the current SUMs literature fit into four categories: (1) Small sample sizes or short experimental durations, (2) high exposure of users to interactions with research staff leading to potential behavior modifications, (3) a lack of SUMs-supported studies measuring factors influencing adoption, and (4) the general dearth of SUMs data needed to understand a problem as complex and contextually heterogeneous as cookstove adoption. The Berkeley Air (2013) study employed only 25 participants, and the Thomas et al. (2013) study follows stove users for only 2 weeks. In the Ruiz-Mercado et al. (2011, 2013) and the Thomas et al. (2013) studies, relatively high levels of adoption were observed, but this was in the context of significant exposure of study participants to field staff. Thomas et al. (2013) found small but statistically significant declines in usage over the course of the 2 weeks following sensor implementation, potentially due to the saliency of observation [as seen for exercise in Prestwich et al. (2009) and savings in Karlan et al. (2010)]. To date, SUMs have been implemented at small scales and in relatively few contexts. Cookstove adoption is a contextually heterogeneous problem owing to the high variability of cooking environments (e.g., cultural, economic, and culinary factors). Therefore, regardless of shortcomings of previous work, the literature contains a dearth of objective information on cookstove adoption objectively measured by sensors.

In this study, we seek to improve upon previous work while adding critical information to the small pool of studies objectively measuring cookstove adoption with SUMs. We add significantly to the existing literature by measuring: (1) Adoption of cookstoves in an internally displaced people's (IDP) camp context and (2) the correlation between user-reported and sensor-measured cookstove adoption both in terms of number of cooking events and hours spent cooking per day. The Berkeley-Darfur Stove (BDS) is the subject cookstove of this study. Scientists and students at University of California, Berkeley and Lawrence Berkeley National Laboratory (LBNL) developed the BDS for assembly, dissemination, and use in the Darfuri cooking context. Potential Energy, a nonprofit headquartered in Berkeley, manages the implementation of the BDS. Going by the Arabic nickname "5-Minute Stove," the BDS is valued by customers for being a fuel-efficient and fast-cooking stove. Between 2009 and 2013, more than 34,000 BDSs were distributed in North Darfur to rural, urban, and internally displaced households. About 85 % of these cookstoves, including those employed in this study, were disseminated free of charge.

20.2 Design and Methods

The Darfur SUMs experiment involved 180 women within the Al-Salam IDP camp just outside of Al-Fashir, North Darfur. Al-Salam is made up of five "administrative units" that represent the geographical origin (before moving into the camp) of the residents within the units. The 180 women were selected by the typical means of BDS dissemination in the IDP camps: a coordinating meeting was held with the chief Omdas (leaders) of the each of the five administrate units, and each Omda was asked to select women for the study from a master list of residents within their unit. Each Omda was instructed to select 36 women that would participate in the study and that would be available during the period of surveys (i.e., would not be moving away from the camp soon). Chief Omdas were provided with the schedule of the surveys and informed selected participants of the dates of baseline and follow-up surveys. Both baseline surveys and follow-up surveys took place in a women's center within Al-Salam camp. Enumeration teams performed a baseline survey of household demographics and cooking practices at the time of BDS dissemination. Dissemination took place over 5 days (one administrative unit per day) between 28 July and 1 August 2013. Subsequently, starting in late August, one administrative unit was followed up with and given a follow-up survey roughly every 2 weeks until late October 2013. At the time of the follow up, SUMs data were downloaded from instrumented stoves. No training on stove use, urging, or inducement to use the stove was administered during the follow up; women simply answered questions such as "how many times per week do you use your stove?" while in the presence of roughly 35 peers who were queued to individually answer the same questions with one of three enumeration teams. Participants were interviewed individually, but potentially within earshot of one another.

Of the 180 participants, 170 women had instrumented cookstoves. Ten cookstoves were left uninstrumented in the case that some participants declined to consent to participate in the research at the time of dissemination (none declined). SUMs fit into one of three functional categories: Primary SUMs that sample as fast as possible while still collecting data over the full deployment period (i.e., not running out of memory), moderate sampling rate SUMs that sample once every 3 min, and fast sampling "piggyback" redundant sensors that validate data from a primary SUM. 190 SUMs were mounted to the 170 instrumented cookstoves with 20 cookstoves having two SUMs each (one primary and one "piggyback") and the remaining 150 cookstoves having one SUM and one "dummy SUM" that appeared identical to a true SUM, but contained no sensor. Following previous work by Ruiz-Mercado, Berkeley Air, and Levine, the sensor within the SUM, shown in Fig. 20.1,

Fig. 20.1 SUM assembly showing the primary case, iButton, spring, and cap

Fig. 20.2 Women participate in enumeration activities while BDSs wait to be taken home. Human subjects' faces have been hidden; enumerators' faces are shown

was Maxim Integrated's DS1922E high-temperature iButton with 8 kB of memory and a temperature logging range of 15 °C–140 °C in 0.5 °C increments.

As pictured in Fig. 20.2, baseline and follow-up surveys were administered by teams of two enumerators who redundantly recorded responses on paper and on a cell phone platform running Open Data Kit (ODK) (Hartung et al. 2010). ODK would send original survey data back to Berkeley in real time while enumerators performed data entry at a later date (also using ODK) for paper surveys. One peculiar issue encountered during the study was the inability to access and use the Google Cloud Computing-based variant of ODK Aggregate from the study location. As Sudan is on the list of sanctioned nations managed by the United States Office of Foreign Assets Control, many cloud-based technologies are inaccessible. Our solution was to use an Aggregate instance deployed at Berkeley to communicate and collect data from our devices in the field. This scheme also allowed us to retain complete control over the survey data and to reduce network performance issues occasionally encountered with Google AppEngine-based instances of ODK Aggregate. Other possible solutions could have included deploying a local server in country or using a virtual private network (VPN), however this would have required substantial additional training. Upon retrieving survey data, entries were hand-checked for obvious typographical errors (e.g., if the original ODK survey listed a woman's age as 23 and the data entry version listed it as 233, the data entry version was manually corrected). Nonobvious incongruences were not manually corrected.

SUMs data were analyzed over the period from the first midnight after a Unit's last baseline survey until three midnights before a Unit's first follow up survey. The padding preceding the follow up survey is to ignore pre-survey courtesy uses.

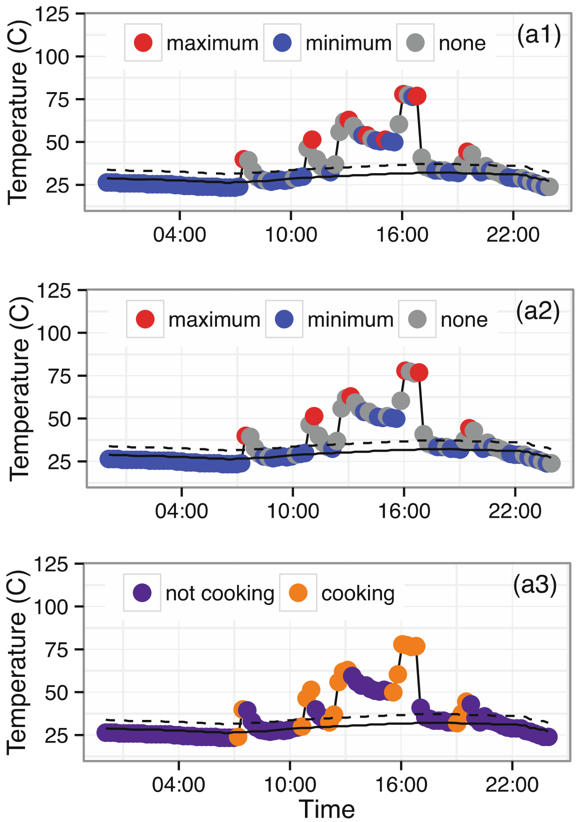

Fig. 20.3 Boxes (**a1**–**a3**) illustrate the event detection algorithm over a one-day period for a particular SUM. Ambient temperature is shown as a *black line*, 5 °C above ambient is shown as a *dashed black line*. For fully-processed data shown in figure (**a3**), non-cooking events are shown as in *purple dots*, and cooking events in *orange dots*

SUMs data were labeled as cooking or not cooking using the following algorithm: First, minimums and maximums were calculated and labeled using a moving window of approximately 30 min. Maxima not more than 5 °C above ambient were eliminated. Points not more than 1 °C above the local minima were also labeled as minima. The initial set of extrema identified by these rules can be seen on an example day in Fig. 20.3a1. Next, each sensor was processed going forward through time to eliminate spurious extrema with the following rules: (1) To eliminate maxima due to heating not caused by cooking in the stove, maxima less than 5 °C above the previous minima, and maxima with ramp rates less than 0.2 °C/min relative to the previous minima were eliminated; (2) To eliminate minima due to fluctuations in cooking temperature expected when cooking with biomass, minima that were within 20 % of the previous maxima (relative to the previous minima) were eliminated. The remaining extrema are shown in Fig. 20.3a2. Third, runs of consecutive minima and runs of consecutive minima were consolidated to identify the start and end of cooking events, respectively. Runs of maxima were consolidated by selecting the last maxima in a run not less than 80 % of the highest maxima (relative to the previous minima), and runs of minima were consolidated by selecting the last minima in a run that was either not more than 10 °C above the lowest maxima or not more than 10 °C above ambient. Finally, all points from each minimum to the next maximum were labeled as cooking. The final labeling of cooking and not cooking is shown in Fig. 20.3a3.

Generally speaking, these algorithm labels event when the cookstove's temperature is increasing rapidly due to a fire or times where the cookstove is cooling intermittently before a refuel. This algorithm is conservative in terms of cooking duration and may overestimate the number of individual cooking events especially for cooking behaviors where the stove is allowed to cool substantially (>80 % of the difference between peak temperature and ambient) before fuel is reloaded. Applying this algorithm to data from all sensors, the resulting labels of cooking events had good face validity and no obvious systematic errors.

20.3 Results

Primary cooks in the SUMs experiment had ages ranging from 18 to 75 with a median age of 34.5. Household size, defined as "number of people who eat from the same pot," ranged from 3 to 20 with a median of 7 members. Most households had similar numbers of men/women and boys/girls (under 14) with a median household having 2 women, 2 men, 1 girl, and 1.5 boys.

180 women participated in the baseline survey and 171 participated in the first follow up. Of the 190 sensors sent to Darfur, 137 survived to the first follow up. These 137 SUMs represent 122 unique cooks; 15 of the surviving sensors were redundant "piggyback" sensors. Of the 122 unique cooks who had instrumented stoves and returned functioning SUMs, 117 were administered follow-up surveys. Figure 20.4 illustrates the fate of the 190 sensors. By far, the greatest contributor to loss of SUMs was unrecoverable data due to thermal damage. 31 SUMs from 29 unique cooks showed likely signs of thermal damage: 28 SUMs were lost due to dead batteries or unreadable iButton memory chips (Maxim states that overheating can substantially shorten iButton battery life, destroy memory chips, or both) and an additional 3 sensors showed signs of physical thermal damage including charring or

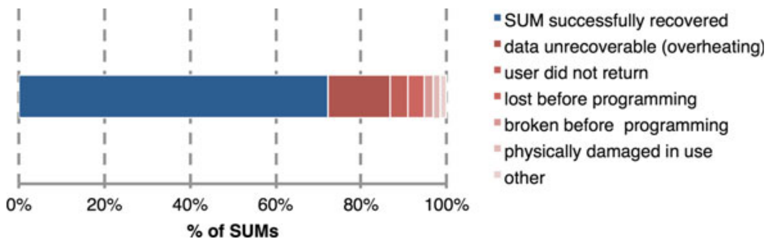

Fig. 20.4 The fate of the 190 SUMs deployed to Darfur. *Blue* represents SUMs successfully recovered at the first follow up. *Shades of red* represent SUMs lost to various causes. The most significant cause of SUMs loss was unrecoverable data due to overheating

rupturing of the iButton housing. The team had performed a substantial number of experiments to determine appropriate placement of the SUMs to prevent overheating, therefore the loss of so many SUMs was puzzling. However, our team later determined that many cooks invert the BDS and fill the bottom with charcoal to cook. This user-led innovation allows cooks to utilize the BDS as an improved charcoal stove, but this behavior also overheats the SUM. One ramification of unrecoverable data from overheated SUMs is that users who exhibit behaviors that overheat their SUMs are systematically underrepresented in SUMs data. We expect that cooks using their cookstoves often, at high temperature, and inverted are likely to have a much higher SUMs burnout rate than cooks who do not use their stove regularly. For this reason, we believe that the data we show herein generally underestimates the adoption of the BDS by the population. Furthermore, we are able to put an upper bound on the magnitude of underestimation resulting from the higher SUMs burnout for adopter cooks than non-adopter cooks. Unless mentioned otherwise, the rest of the analysis in this paper assumes no bias in the estimates obtained from the SUMs.

Using the definition of a cooking event discussed in the methods section (Sect. 20.2), a determination was made between cookstove "users" and "non-users." The distinction between a "user" and "non-user" was determined by the proportion of days that the stove was used. In order to account for "courtesy" uses immediately before a follow up, a 2-day period preceding the first follow-up survey was ignored. For the purposes of this analysis, a demarcation between "user" and "non-user" was made at 10 % of possible stove use days during the observed period (i.e., if a participant used the stove less than 1 in 10 days, she is categorized a "non-user"). This classification is arbitrary and used only as a metric by which to separate women who regularly use the stove and those who use it very little or not at all. Using this classification, 71 % (87 participants) are categorized as "users" and 29 % (35) as "non-users." To obtain an upper bound on the bias effect from higher SUMs failure rates with "user" cooks, we recalculate this percentage assuming that all the thermally-failed SUMs were with the "users" group. This leads to an upper-bound estimate of 77 % (116) users and 23 % (35) nonusers. For those participants with surviving sensors, a summary of SUMs-measured cooking behavior is tabulated in Table 20.1.

The algorithm employed in this analysis detected 7,358 individual cooking events with average event duration of 39 min (SD = 26 min) over the timeframe SUMs were analyzed. A histogram of event durations is shown in Fig. 20.5.

Participants in this study overestimated their BDS usage in surveys both in terms of events per day and total cooking time per day. Relative to algorithmic estimates, 84 % of participants overestimate cooking hours, and 81 % overestimate cooking

Table 20.1 Summary data for all participants, users, and nonusers

	All subjects			Users			Nonusers		
	n	Mean	SD	n	Mean	SD	n	Mean	SD
Hours	122	1.1	1.1	87	1.5	1.0	35	0.028	0.063
Events	122	1.5	1.4	87	2.0	1.3	35	0.036	0.076

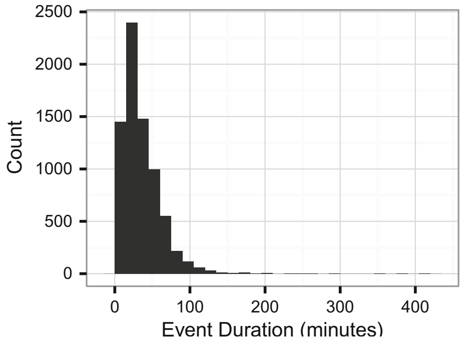

Fig. 20.5 Histogram of the duration of 7,358 individual cooking events

events. The average participant overreports daily cooking hours by 1.2 h with 95 % CI [1.0, 1.4] and overreports her daily cooking events by 1.3 events with 95 % CI [1.1–1.6]. Nonusers overreport their daily use more substantially: 1.7 h with CI [1.4, 2.1] and 2.2 events with 95 % CI [1.9, 2.6].

For the two survey questions analyzed, 160 surveys were available that had copies of both original ODK data and data entry versions of paper surveys. Of the 320 total answers between the two questions, there was only one disagreeing pair between original ODK data and pencil and paper data later entered via ODK.

20.4 Conclusions

The combination of SUMs and an algorithm for cooking event detection has provided a detailed record of the frequency, timing, and duration of cooking events from a large number of users. The experimental population is a representative proxy for the population that has received the BDS free of charge in Darfuri IDP camps. Although the BDS units distributed in this study were free of charge, 71 % (conservative) to 77 % (upper bound) of participants were categorized as “users” by the definition used in this study indicating that this stove is valued by the women who own it. Qualitatively, BDS adoption in the Al-Salam IDP camp is high considering that women receiving the stove were selected at random and had no personal monetary investment in the product.

The juxtaposition of paper and cell phone-based surveys against SUMs data has highlighted the discrepancies self-reported versus sensor-measured usage patterns. Data from both the paper and cell phone-based surveys was consistent, and in surveys participants overestimate adoption both in terms of hours and events ($p < 0.001$) relative to the SUMs algorithm. Average participants overreport daily cooking hours by 1.2 h and daily cooking events by 1.3 events, and nonusers overreport daily cooking behaviors more dramatically than the average participant: 1.7 h and 2.2 events. For the average participant, these overestimations are roughly double the SUMs-measured values for hours and cooking events, and for nonusers overestimations are 60-fold higher than SUMs-measured values for hours and events cooked per day. Data reported by the participants may be erroneous due to difficulty in recollection, courtesy bias, or the desire to keep personal information obscure (e.g., as reported by field staff, respondents may try to obscure true household size by misreporting cooking hours) These findings herein indicate that data from SUMs are more detailed, accurate, and meaningful than self-report use data, and should be preferred as a gold standard for future studies of stove use.

A portion of SUMs was lost during this study, presumably due to thermal damage from charcoal fires. For future studies, SUMs placement must be altered to avoid damage. Additionally, Potential Energy may consider a redesign of the BDS to better accommodate users' desire to burn charcoal in the BDS.

A major question unanswered in this work is the correlation between the start and stop times of algorithm-determined cooking events and "true" witnessed cooking events. While the event detection algorithm seems to perform well in terms of face validity, absent a database of cooking logs or witnessed accounts of cooking, the algorithm should be trained against expert-labeled data for the local cooking context to further refine its performance.

Acknowledgments Authors gratefully acknowledge financial support from multiple sources for this work. The primary funding for this work comes from a DIV Phase-1 grant by the United States Agency for International Development (USAID) to Potential Energy. Daniel Wilson and Angeli Kirk are grateful for support from the National Science Foundation (NSF) Graduate Research Fellowship. Additional funding for personnel and materials for this project has been generously provided by funding agencies including the Development Impact Lab (USAID Cooperative Agreement AID-OAA-A-13-00002) which is part of the USAID Higher Education Solutions Network, the Blum Center for Developing Economies, a Behavioral Sensing Grant from The Center for Effective Global Action (CEGA), and Department of Energy Contract DE-AC02-05CH11231 to Lawrence Berkeley National Laboratory (LBNL), operated by the University of California.

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