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Smart Phones as a Viable Data Collection Tool for Medical Record Keeping in Low-Resource Settings: Case Study of Rwandan Children Growth Charts

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Smart phones as a viable data collection tool for medical record keeping in low-resource settings: case study of Rwandan children growth charts

by Suzana Brown

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Smart phones as a viable data collection tool for medical record keeping in low-resource settings: case study of Rwandan children growth charts

written by Suzana Brown

has been approved for the Interdisciplinary Telecommunications Program

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(Alan Mickelson)

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(Zoya Popovic)

Date

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

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Smart phones as a viable data collection tool for medical record keeping in low-resource settings: case study of Rwandan children growth charts

Thesis directed by Associate Professor Alan Mickelson

This thesis proposes an implementation of smart phones as a data collection tool for medical record keeping in low-resource settings. Those devices would collect medical data and store it as an Electronic Health Record (EHR). In community care, EHR could be a bridge from untrained Community Health Workers (CHWs) to healthcare providers with timely and relevant data. Although CHWs are the backbone of health care delivery in developing countries, they often have little formal education and training. Providing CHWs with appropriate training and workplace tools could improve their ability to provide quality community based care. The field work for the thesis was carried out on site in Rwanda, a country with one of the world’s lowest doctor to patient ratios, where CHWs play an important role in healthcare delivery.

The analysis has a multidisciplinary approach, and it evaluates the feasibility and usability of a specific mobile health application. During the field study, CHWs were effective in data collection, collecting close to 2000 records from boys and girls under the age of five. The pilot project included only 24 CHWs but the scaling up estimates are encouraging for the whole of Rwanda as well as other developing countries with health systems similar to Rwandan.

Data analysis presents the evidence that these new electronic records are superior to the currently paper-based records, and demonstrates that electronic records facilitate the development of a country-specific model based on the collected data that is more accurate than the international standard provided by the WHO growth chart. In addition, the electronic collection of data allows real-time monitoring.

Comparing the cost and benefits of the suggested mobile application by calculating a benefit-to-cost ratio, for a present day Rwanda, results in a ratio that has seven times higher benefits than cost. That is a significantly high ratio, however, a concern is that the timing of the cost and benefits differ, and a business model is developed that offers a solution on how to fund costs at the present time without waiting for the future benefits.
Acknowledgments

I was extremely fortunate to have an opportunity to work with Professor Alan Mickelson as my academic adviser. Professor Mickelson stepped in as my advisor at the point when I was already in Rwanda struggling with the field work. He had made the journey possible with his insightful advises and visiting Rwanda to lend me support during the first training with the study participants. Without his wisdom, support and prompt responses to my frantic emails I would have never discovered the value of field research and finished this work.

Another indispensable person to this work was the Director of Carnegie Mellon in Rwanda (CMU-R), Bruce Krogh, who supported my research in many ways: providing financial support; insightful guidance; and who helped me navigate the administrative and cultural issues in Rwanda. Along with Dr. Krogh the following Masters students at CMU-R made invaluable contributions by providing language and programming support along the way: Richard Ishimwe, Bertin Mpagazi, and Kevin Rudahinduka. From the Rwandan administrative side two people stand out with their significant contribution: Frank Shumbusho and Dr. Osee from Kibagabaga hospital. I was also lucky to have a CMU-R visiting professor, Patrick McSharry, teach me about data analysis and one of the chapters in this dissertation is a product of joint work with Professor McSharry.

From the University of Colorado Boulder, I am beholden to Professor Zoya Popovic for her coaching with the final document of this dissertation, without her guidance I would be lost. In addition, I would like to thank the rest of my wonderful PhD committee for being patient, responsive and supportive in this unconventional work.

Emotional support of my two sons, Albert and Viktor Brown, and their father Timothy Brown, was essential for this journey. During my work in Rwanda an invaluable group of friends helped me keep my sanity, among who stand out Gang Seok Lee, Barrett Nash, Chystina Russell, Jenny Aston (also as my English editor), and Alain Shema.
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1 Introduction
Developments in information and communication technology (ICT) have changed the way people communicate by enabling transmission speeds and breadth of coverage never seen before. In healthcare, ICT are providing a variety of new applications that are influencing the way people view health services. Over the past 100 years, the health of the world’s population has been improving but unevenly with a gap between developed and developing countries growing larger [1]. The new ICT developments are promising to provide tools to health practitioners and populations to improve the health outcomes in developing countries in particular. This thesis presents results from a study using a novel application of mobile communication, which provides a tool for medical record keeping in low-resource settings. The field work for the thesis was carried out on site in Rwanda, a country with one of the world’s lowest doctor to patient ratios [2].

1.1 Problem
Access to healthcare is a problem in many developing countries and is often limited by a shortage of healthcare workers [3]. In situations when healthcare workers are scarce, preventative care suffers in particular, and preventative care is important for children because following children’s growth and development can significantly improve health outcomes and overall wellbeing. In developing countries, malnutrition is one of the issues that affect children. Risk of malnutrition is high in Rwanda, with Rwanda ranking 18th on the world scale of malnutrition [4]. Close to 40% of Rwandan children are stunted, a sign of chronic malnutrition [5]. To address such issues, the Rwandan Ministry of Health (MOH) created a program of community health workers (CHWs) in an initiative to improve the population’s health status by ensuring access to preventative and curative healthcare services. The CHWs are elected by their community and work as volunteers. Their activities focus mostly on children’s health, vaccination, and malnutrition, as well as community-based activities around hygiene and sanitation. They also report disease epidemics in their area of coverage, and presently there are total of
40,000 CHWs in Rwanda. However, CHWs have insufficient training and skills, and use only basic workplace tools [6]. In this thesis a solution is proposed that can improve efficiency and effectiveness of CHWs in the domain of health data collection.

1.2 Proposed solution
This study proposes an implementation of smart phones as a data collection tool for medical record keeping in low-resource settings. Those devices would collect medical data and store it as an Electronic Health Record (EHR). In community care, EHR could be a bridge from untrained CHWs to healthcare providers with timely and relevant data. Although CHWs are the backbone of healthcare delivery in developing countries, they often have little formal education and training. Providing CHWs with appropriate training and workplace tools could improve their ability to provide quality community based care [7].

Enabling CHWs to collect medical data using mobile devices and store them as EHRs requires technology adoption by users with very little ICT literacy. This thesis presents a case study in which participants with no previous experience are trained to use smart phones for medical data collection. Then it assesses the feasibility and usability of the implementation in terms of three attributes: effectiveness; efficiency; and satisfaction. In addition, a portion of the thesis addresses data quality component by comparing the quality of traditional paper-based records to the new electronic records.

Transition to EHRs requires considerable investment and one chapter of this thesis presents a cost benefit analysis that will show if the benefit-to-cost ratio justifies such intervention. Sustainability and scalability are issues that are discussed and an entrepreneurial business model is presented that could provide a way to generate the required funds in a timely manner.

During the study there were many challenges, and the next section presents three main challenges that required creative solutions, which are the contribution of this work.
1.3 Challenges
There were three main challenges encountered in this study that required innovative solutions: 1) designing training material for the education of the users with no previous experience with smart phones; 2) implementation in a country with unreliable telecom networks; and 3) design of the business model that would support the wider implementation.

The implementation of the proposed solution required developing an extensive training plan in a local language for the users with no previous experience with the devices and a low education level. That was accomplished by first testing a design for the trainings on a pilot group of users prior to training the actual participants (CHWs). The group was composed of subjects with no previous experience with smart phones and a comparable education level to CHWs. Once we started the actual training of CHWs the content of the training plan was iterated several times and a total of eight trainings executed. The translation to a local language was done by CMU Rwanda Masters students named in the section 1.5.

The field study was completed in Rwanda, a country with unreliable telecom networks, but with an extensive coverage. In order to accommodate an unreliable network environment, a delay tolerant application for the mobile phone was designed. The algorithm is presented in Chapter 4, Figure 4.4.

Designing a business model that would support implementation in the near future requires developing a business model that would generate funds available earlier then the benefits, which would be realized many years from now. In Chapter 6, section 6.4 presents an outline of the business model that offers such a possibility.

The following section presents a list of papers published during the course of my graduate work and it details the contribution of each author.
1.4 Papers and Contributions

My research in the last three years has resulted in many papers and in this section they are presented along with the contributions of each author.


Contributions—S. Brown performed the data analysis and wrote the manuscript; Mpagizi managed raw data collection and storage; McSharry advised on the choices of analytical tools and edited the manuscript.


Contributions- S. Brown wrote the manuscript and performed the analysis; Rudahinduka obtained the required permissions from the hospital and the Rwandan Ministry of Health, and preformed the interviews with the doctors.


Contributions –S. Brown organized and wrote the manuscript; Umutoni organized and systemized the references and contributed to one section of the paper.

Contributions – S. Brown developed the theoretical model and wrote the manuscript; T. Brown suggested the structure of the model.


Contributions – S. Brown and M. Saint conducted the lab experiments, designed data visualization, and wrote the manuscript; T. Brown advised and suggested the research question and data interpretation.


Contributions – S. Brown developed the model and wrote the manuscript; M. Saint suggested modifications and edited the manuscript.

### 1.5 Thesis organization

The specific approach taken in the thesis is to 1) investigate the attitudes of doctors and CHWs toward the use of mobile devices in the health sphere, by survey and interview, 2) implement an electronic data collection system in two Rwandan communities using an original delay tolerant smart phone application, 3) collect electronic health data on children’s growth and development for nine months and then 4) analyze the collected data comparing it to the paper-based data records while 5) generating a sustainable business model and 6) calculating a benefit-to-cost ratio to investigate value of the project.
The most significant contribution of this thesis is an implementation of the novel mobile application for collecting data on children’s growth and showing that such data has higher usability than paper–based data and the World Health Organization standard for children growth charts.

The field study was completed in Rwanda and translations and trainings in a local language were performed by CMU Rwanda students Richard Ishimwe and Bertin A. Mpagazi. Richard Ishimwe also executed programming tasks related to the mobile application. Another field implementation for this study includes survey of doctors from the King Faisal hospital in Kigali, and the actual survey was executed by a CMU student Kevin Rudahinduka.

The next chapter in this thesis, Chapter 2, gives an overview of published literature in the different areas related to the thesis. Chapter 3 presents the complete model for enabling data collection with mobile devices and storing them as EHRs from technical, operational, data analytics and business perspectives. Chapter 4 discusses the adoption of telecom technology in the healthcare space, and then the usability of one particular mobile application designed to collect medical data. Chapter 5 outlines a general framework for comparing data quality using electronic tools, such as modern telecommunications equipment, and paper-based collection. Chapter 6 offers a model for cost-benefit analysis of an investment in monitoring the growth of children and proposing a business model that would generate funding. Finally, Chapter 7 presents future work and concludes.

1.6 References:


2 Literature Review and Background
This chapter gives an overview of published literature in the different areas related to the thesis: 1) prior research in mHealth; 2) technology adoption studies; 3) electronic data collection; and 4) sustainability of ICT for Development (ICTD) projects, and specifically cost/benefit analysis of mHealth projects. Each section has a table summarizing papers most relevant for this thesis. Within the same section, there is a detailed analysis of the literature from the tables along with additional papers that are important in the field but are not as closely related to this study.

2.1 Literature on mHealth Studies
There are four distinct areas of mHealth: monitoring and data collection; adherence to medication or treatment; health education; and mobile phones as medical devices. The research presented in this thesis falls into the first category of monitoring and data collection. For that reason, this section is divided into two subsections: one that provides evidence-based research concerning the use of mobile phones for monitoring and data collection in healthcare from related studies, and another that summarizes all other types of mHealth studies related to adherence to medication or treatment, health education, and mobile phones as medical devices.

2.1.1 Monitoring and data collection
Table 1 summarizes significant literature in the area of monitoring and data collection and its relationship to this thesis. Along with the studies directly related to monitoring, the research on EHR is included because it is a necessary enabling technology for digital medical data collection. Papers in Table 1 show that mobile technology is an effective way to monitor and collect health data and that EHRs are an efficient way to store and access that data.
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<td>Turner-McGrievy et al.</td>
<td>J Am Med Inform Assoc. PubMed Central PMCID</td>
<td>Shows that mobile phone apps are more effective than traditional monitoring methods such as paper journals.</td>
<td>Comparing two different data collection methods, paper and electronic.</td>
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<td>“Designing and Implementing an Innovative SMS-based alert system (RapidSMS-MCH) to monitor pregnancy and reduce maternal and child deaths in Rwanda”</td>
<td>J. Nguimfack et al.</td>
<td>PanAfrican Medical Journal, ISSN 1937-8688,Oct. 2012</td>
<td>Presents findings that monitoring pregnant women using SMS reduces maternal and child death.</td>
<td>An emergency alert system compared to monitoring children’s health. Both studies were in Rwanda.</td>
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<td>“Experience in implementing the OpenMRS medical record system to support HIV treatment in Rwanda”</td>
<td>C. Allen et al.</td>
<td>Stud Health Technology Inform. Vol. 129, pp. 382-6, 2007</td>
<td>Proves that a digital medical record system for HIV leads to improvements of health systems in limited resources.</td>
<td>Evaluates impact of one EHR in Rwanda, the present study designs the EHR.</td>
</tr>
<tr>
<td>“Exposure to anti-malarial drugs and monitoring of adverse drug reactions using toll-free mobile phone calls in private retail sector in Sagamu, Nigeria”</td>
<td>A. Adedeji et al.</td>
<td>Malaria Journal, 10:230, pp. 1-6, 2011</td>
<td>Tests use of mobile phone technology for drug exposure and collects data on ineffective malaria drugs.</td>
<td>Monitors drugs while the present study monitors children, both in developing countries.</td>
</tr>
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Table 1 Summary of literature on monitoring in mHealth and Electronic Health Records (EHR).
Reviewing the papers from the above table starts with a seminal work by Wesolowski et al., who assumed that the mobility of people from high malarial risk sites to low malarial risk sites increases the risk of contamination in the low risk sites [1]. Researchers were able to obtain data on the movement of mobile phone owners and travel information from thousands of individuals under observation. The authors tracked, observed and analyzed travel patterns of individuals from origin to destination. This kind of research couples big data from mobile phones with detailed malaria incidence information from malaria centers, and promises to become an important tool for understanding disease spreading.

Another research group carried out a study [2] to assess the relationship between the self-monitoring of diet and physical activity. They tested mobile apps alongside other methods, such as paper journals, and a comparison of results showed that people who used the diet app had better adherence than the ones who used paper journals. The authors concluded that mobile phone apps are more effective than traditional monitoring methods for monitoring diet and physical activity.

A project in Rwanda, described in [3] monitored pregnant women with the goal of reducing maternal and child death, with an interesting conclusion that the implementation of a rapid SMS alert system produced a 27% increase in facility-based delivery with a growth from 72% to 92% in the one-year pilot phase, alongside 362 SMS emergency alerts. This SMS system allows real-time two-way communication between Community Health Workers (CHWs), ambulance workers, health facility staff, the District Hospital and Central Facility.

The preference for mobile phones as a mode of communication can be attributed to the personalized information they can provide. A study [4] that identifies mobile preferences in health applications by Nithya et al. concludes that individualization, context-awareness, real-time feedback, and tailored intervention delivery are key features that reduce user burden and increase acceptability and attractiveness.
Remote monitoring using real-time information from wearable and non-wearable sensors, mobile phones and other sophisticated devices provides vital signs needed for emergency responsiveness, especially among elderly or chronic patients. Although the focus of mHealth interventions has been on chronic conditions, there is a need to discover the impact of mHealth in monitoring acute conditions, and along with this to ascertain whether mobile phones are the ultimate tools to address the real-time specific needs of patients experiencing acute conditions.

Real-time monitoring provides vital information for authorities in the early detection of diseases. In an article [5] published by Meibner et al. from the UK Royal Academy of Engineering on mobile phones and medicine, Dr. Elliott, an aerospace engineer, noted that he is now part of a small Swiss company developing sensors that could put a blood pressure monitor inside every mobile phone. This enables the provision of guidance in emergency responsiveness. Another example is the “Gluco Phone” cited by Hareyan [6] developed for patients with diabetes to monitor and transmit glucose information to caregivers while also reminding patients when they need to undertake glucose tests. A related scenario would involve sensors recording calorie intake for weight loss participants. A customized feedback calling users by their name increases the likelihood of positive response.

A study carried out in Rwanda “Experience in implementing the OpenMRS medical record system to support HIV treatment in Rwanda” [7] considers how the problems of scaling up HIV treatment in Africa has led to improvements of health systems in resource-limited areas. One aspect is the improvement and deployment of EMR systems. In this paper [7], the authors describe the design and implementation of a new EMR system for an HIV treatment in rural Rwanda. The system is called OpenMRS and it addresses the problem of configuring EMR systems to suit new sites, languages and diseases. OpenMRS uses a concept dictionary to represent all the possible data items that could be collected. One advantage is that new items can be added to the system by non-technical personal. It
also contains a form creation tools that use drag and drop web technologies to simplify the process. The OpenMRS system was first introduced in 2006 in Kenya and soon after in Rwanda. The system is now functioning well with some extensions to improve the support for the clinic, such as reporting tools, help with nutrition and child health, database synchronization tools, and modules to collect laboratory data and support the pharmacy. The system is also in use in South Africa, Lesotho, Tanzania and Uganda.

As the need for monitoring accelerates there is a continuous demand for mass monitoring, such as detailed in a study by Wesolowski et al. [1] that linked human mobility with the spread of malaria in Kenya. Another example is a cloud-based, remote monitoring solution commercialized by an American company (Verizon) [8] which will collect and store biometric data from various devices such as a mobile phone, computer or any other electronic device used at home. The device allows automated transmission of data to a server or the cloud, allowing health care providers to analyze and intervene whenever required. However, this solution is heavily dependent on Internet connectivity.

All the previous solutions require user friendly, reliable and affordable designs tailored to the different groups of people. Most of the apps are not designed with end users in mind; there is a need to design applications for all categories of people, for example, the illiterate, the elderly, and patients with disabilities. Putting all these aspects into consideration will facilitate the development of user friendly, diverse and effective solutions.

Despite the rapid growth of mHealth solutions, significant limitations remain. The combination of illiteracy and the use of indigenous languages coupled with network reliability are major issues which currently limit the reach and effectiveness of mHealth. Most of the applications require a network to convey the emergency data and the framework is not particularly robust in remote areas of developing countries where the network is not yet properly established. Additionally, phones require regular charging to maintain battery power. This remains problematic in certain areas, for example, the World
Energy Outlook (WEO) [9] noted that in 2011 the population without electricity in Sub-Saharan Africa was 585 million with the highest concentration of these numbers in rural areas. This can be counteracted by providing biogas energy and solar energy as an alternative to electrical power. The concept of sharing phones amongst villagers also leads to privacy and confidentiality issues.

Adverse drug reactions (ADRs) contribute to ill-health or life-threatening outcomes, and A. Adedeji et al. [10] investigate the use of mobile phone technology to report ADRs following drug exposures in Sagamu, a community in Southwest Nigeria. The findings from this study [10] indicate that ineffective anti-malaria medicines remain widely available and are frequently purchased in the study area. The authors conclude that availability of a toll-free telephone line may facilitate pharma vigilance and follow up of reaction to medicines in a resource-limited setting.

To investigate the feasibility, ease of implementation, and extent to which CHWs with little experience of data collection could be trained, Tomlinson et al. conducted a pilot study [11] in which CHWs collect data using mobile phones in a large baseline survey. They find that mobile technology is a feasible method of data collection that needs to be further explored.

A paper by Freifeld et al. presents a brief summary [12] of promising mobile applications for health monitoring and information sharing, together with preliminary results from a study of smartphone application deployment that enables the general public to report infectious disease events. On the other hand, Kaewkungwal et al. test a mobile application which integrates into the healthcare system to improve antenatal care and expanded immunization for the under-served population [13].

There is no doubt that the increasing global presence of mobile phones paves the way for enhanced healthcare services to individuals and communities, while helping to strengthen health systems. The need to understand the most pressing issues in both developed and developing countries is mandatory and will demand the involvement of a multi-disciplinary enterprise of academicians,
healthcare professionals, patients, and industry regulators working together to develop effective and lasting solutions.

The prevalence of EHR in developed and developing countries, and their impact on the health care services is examined in many studies. Several examples are presented below.

A study in 2009 by Jha et al. [14] surveyed all acute care hospitals that are members of the American Hospital Association for the presence of specific electronic-record functionalities, and found that only 1.5% of U. S. hospitals have a comprehensive electronic-records system, and in addition 7.6% have a basic system. They also find that larger hospitals, such as those located in urban areas, and teaching hospitals were more likely to have electronic-records systems. Their conclusion is that the very low levels of adoption of EHR in U. S. hospitals suggest that policymakers face substantial obstacles to the achievement of healthcare performance goals that depend on health IT.

Another study [15] concluded that effective EHR implementation and networking could eventually save more than $81 billion annually by improving healthcare efficiency and safety. However, the authors predicted that it is unlikely to be realized without substantial changes to the healthcare system. A different study by Wang et al. [16] performed a cost-benefit study to analyze the financial effects of EHR systems in ambulatory primary care settings from the perspective of the healthcare organization. The results show that twelve years ago (2003) the estimated net benefit from using an electronic medical record for a 5-year period was $86,400 per provider.

EHRs could improve healthcare by reducing the time health providers spend on documentation. A systematic review by Poissant et al. [17] examined the impact of EHRs on the documentation time of physicians and nurses. The survey examined 23 papers and found that only studies that conducted their evaluation process relatively soon after implementation of the EHR tended to demonstrate a reduction
in documentation time. In comparison, those that had a longer time period between implementation and the evaluation process failed to do so.

In limited-resource settings, the problems that demand a better record system are different (for example, TB, HIV and malaria) and the objectives are most often related to tracking patients, managing data, and generating reports. For example, Shah et al. [18] examine DataPall, a system developed using design criteria encompassing both functional and technical objectives articulated by hospital leaders and palliative care staff at a leading palliative care center in Malawi. The authors find that the system enabled palliative care providers to find patients’ appointments, on average, in less than half the time required to locate the same data in current paper records.

A group of researchers conducted a systematic review [19] to identify barriers to the implementation of EHR in low-resource settings. The key impediments are technical infrastructure problems, such as unreliable electric power and erratic Internet connectivity, health workers’ limited computer skills and failure by providers to comply with the reminders of the system.

The study from Monda et al. [20] evaluates an approach where built-in functionality within an electronic record system could identify data quality and integrity problems with little human input. Their conclusion is that electronic data collection allows data integrity and quality checks, and they successfully implemented one within an e-health system in sub-Saharan Africa. The tool potentially reduces the burden of maintaining data quality by limiting the scale of manual reviews needed to identify electronic records with errors.

A claim that EHRs will revolutionize healthcare by scaling up treatment programs is presented in [21], and that EHRs will be a key to providing the highest possible quality of care for the funds developing countries can commit to health care. They recommend that public, private, and academic partnerships should facilitate the development and implementation of EHRs in resource-limited settings.
EHRs are still in infancy in developed countries, however, research shows that they can improve efficiency and reduce cost. In low-resource settings, EHRs implemented for collecting data on specific diseases are identified as a way to scale up health services. The barriers to implementation are infrastructure and health workers’ skills related. This thesis will identify issues relevant in training people who never used a particular technology before.

2.1.2 Other types of mHealth studies
There are many other types of mHealth studies, and this section reviews several that are representative for the field of adherence to medication or treatment, mobile devices for health education, and mobile phones as medical devices.

2.1.2.1 Adherence
Among adherence studies there is a subset that specifically deals with adherence applications with an emphasis on limited-resource settings. The word “adherence” means “steady devotion”, and in the medical world it is often defined as following a medical program. The biggest focus of studies is on adherence to medication, defined as the extent to which patients follow healthcare provider prescription to consume medication within a defined period [22].

Adherence research has been focused on medication, but also encompasses numerous health related behaviors that extend beyond taking prescribed pharmaceuticals. In summary, adherence is the extent to which the patient follows instructions or continues a treatment regimen under limited supervision when faced with conflicting demands [23].

The importance of the issue is summarized in a World Health Organization (WHO) report [24]: “Medicines will not be effective if patients do not follow prescribed treatment, yet in developed countries only 50% of patients who suffer from chronic diseases adhere to treatment recommendations. In developing countries, when taken together with poor access to healthcare, lack of appropriate
diagnosis and limited access to medicines, poor adherence is threatening to render futile any effort to tackle chronic conditions, such as diabetes, depression and HIV/AIDS.”

However, there is a recent shift toward a view that medication adherence is not exclusively the responsibility of the patient because medication-taking behavior is complex and it should involve patient, physician, and process components [25]. Process components refer here to the frequency and length of the treatment. The trend is towards reducing the daily doses and shortening the length of the program because of the correlation shown between adherence and the number of pills a patient has to take. Osterberg and Blaschke [22] found that adherence is inversely proportional to the frequency and length of doses. Unfortunately, some of the most serious diseases affecting the developing world, such as HIV and TB, require prolonged regime. It is not surprising that the mHealth projects use these two diseases for the proof of concept that using technology to ensure adherence to medication has a huge benefit.

A prominent study “Real-Time Adherence Monitoring for HIV Antiretroviral Therapy” [26] tests the usefulness of a simple bottle that transmits data when the patient opens it. The system uses GPRS and is tested in a developing country: Uganda. As a proof of concept it shows that the system works 90% of the time and adherence rises up to 100%. The main weakness is that the system is still expensive for limited-resource environments ($185). A similar study [27] named SIMpill was carried out in South Africa to improve treatment compliance amongst 155 TB patients for a period of 10 months. It involved a pill box that automatically delivered a text message to the central server when being opened. The study suggests that SIMpill has achieved between 82-96% drug adherence and a treatment success rate of 94%. Both studies use SMS and GPRS technology, affordable in resource-limited environments.

As adherence to a medical regime is of critical importance when managing HIV/AIDS, many studies have been carried out in the area. In an extensive survey [28] that covered 26 adherence studies,
two were projects focusing on mHealth using text messaging [29] [30]. Another study [31] that looked at the use of mobile phones to call AIDS patients by community health workers, found no significant virologic improvement in patients who received calls but suggested that there was a positive qualitative improvement in care.

Tuberculosis deaths can be attributed to either a lack of early detection or poor adherence to the treatment [32]. Management of the disease is therefore highly human resource dependent, and the shortage of health workers has made TB a major public health concern [33]. A study from the US [34] presents a pilot project using ingestible sensors to monitor adherence to TB medication. Wireless observed therapy (WOT) from this study uses wireless sensors which transfer information from sensors to the mobile phone, further to base station, and via cellular network to the medical provider. This is machine to machine transmission but it requires humans to monitor compliance. At present, such an advanced system is possible only in a developed economy because of the cost associated with digestible sensors and WOT.

Tuberculosis patients must finish a full course of treatment in order for it to be effective, so a paper by Kittusami [35] explores the role of a mobile phone in sending reminder messages not only as a trigger to alert the patient to take medicines but also to educate them about TB related problems [33]. The modes of data transport are text messages and phone calls via mobile phones. Another feasibility study for compliance to TB treatment [36] in Kenya is called the “Mobile Direct Observation Treatment (MDOT) of Tuberculosis Patients”. This study observed thirteen TB patients who were asked to video-capture themselves while taking the medication, and then send the video to the corresponding healthcare facility. The constraint is that it requires mobile phones that have video recording capability.

For the same medical issue, TB, in resource-limited settings the appropriate technology available in the developing world, are GPRS or SMS, while in the wealthier countries ingestible sensors and wireless detection are used.
For adherence to supplements, a study by Niranjan et al. [37] describes the use of an automated voice call by pregnant women to receive short audios encouraging them to take iron supplements. Furthermore, in other studies [38] the concern is cognition performance in older adults and an increase in injuries and falls, both requiring regular exercises to improve health and well-being. The researchers use tablet applications to motivate older people to follow personalized training plans autonomously at home. They demonstrate its effectiveness in gait speed improvement through the evaluation of performance data from 44 adults that followed a 12-week strength and balance training program [25].

Work by McGillicuddy et al. [39] developed an application that enables the self-management of blood pressure using a patient centered design. The development framework utilized self-determination theory with iterative stages that were guided and refined based on patient and provider feedback. A 3-month proof-of-concept randomized controlled trial was conducted in 20 hypertensive kidney transplant patients identified as non-adherent to their current medication regimen based on a month long screening using an electronic medication tray [39].

From the developed world, pilot studies often involve the use of technologies such as WiFi and sensors to keep track of compliance to exercise and weight loss programs. In resource-limited settings, SMS and GPRS are the main solutions. However, both developing and developed countries use mobile phones, albeit in different ways. In developed countries the phones are smart, while in resource-limited settings phones are predominantly still feature phones with voice and texting as a mode of communication.

2.1.2.2 Health Education
With the development of mobile usability and the amelioration of the user interface, the convenience of using mobile phones is continually influencing the way we learn today. Fontelo et al, looked at the various ways in which mobile devices can be used in medical schools; some of these included healthcare
providers sharing and learning through blogs, wikis, podcasts, and social media, using Learning Management Systems (LMS) and using mobile devices for patient tracking [40]. Similarly, Ducut et al. conducted a study on how mobile devices can be used in medical education [41]. There have also been interesting new ways of delivering medical education developed through games such as that shown in the study of Grimes et al., who created a mobile game called OrderUp in which players learn how to make healthier meal choices [42].

Furthermore, games are being used for simulations to enable medical students to practice and learn. For example, Trauma Center Wii game [43] can be used as a simulation for medical students to practice surgery which can help to reduce errors by learning through the simulation. Such games or simulations are being extended to mobile devices such as tablets [44], which are commonly preferred by healthcare providers and medical students because they have good screen resolution, larger screen size and better battery life than phones. Entertainment Software Association reports that 36% of gamers in 2013 played games using their smart phones [45]. Medical education games have the potential to reach many gamers who would benefit from playing games and at the same time learn about their health. As an outcome more game simulators are designed for different industries and particularly within health education [45] whereby games can be used to help students learn as the video games are built with the intention of challenging the ingenuity of a person. While there are many great opportunities with mobile devices in medical education, there are some limitations that should not be ignored.

The use of mobile devices in health education presents many limitations related to the design and the content [46]. Although the content may be delivered in various ways, including by SMS and LMS, as well as any combination of these programs, the use of mobile device possess some specific design challenges, such as limited screen space, device-specific operation systems, unique navigation methods, and certain program incompatibilities such as running flash player on Apple iPads [47]. Such issues may
be resolved through having standards in place which will likely come with the growth of mHealth field; however content design may be the biggest limitation. Every geographical location may have its own specific need which means that there is no size that can easily fit everyone. Every solution that may have worked somewhere else may require customization because of the type of mobile devices that are used. Coming up with the right content for a certain area is critical and this requires having skilled and experienced labor. Another limitation may be related to cost, especially within developing countries that have challenges with electricity, access to Internet and a small number of smart devices which are commonly preferred because of their capabilities to engage the learner using advanced graphics and various media.

From the perspective of health education, both types of environments can benefit from improved content and more customized material. The technology choices seem to be mobile phones with their ever advancing features such as an increase in processing power and storage, and in particular, smart phones that can handle various media. There are very few choices of educational content on feature phones and they are limited to informational text messages.

2.1.2.3 Mobile phones as medical devices
A key factor in the promotion of mobile phones as medical devices is the advancement in their processing power, hardware and software. Originally produced solely for the purpose of communication, these devices can now be used for medical diagnostic purposes as well. Mobile devices can either be used with applications or with additional attachments to enhance functionality. These are low-cost, highly effective devices that can replace large, heavy and expensive medical equipment. This allows patients to have access to medical devices or enable caregivers and physician working in remote, low-income settings to have first-hand medical information.
Considerable research has been done in this field mostly around prototypes. Richard et al. [48] examined the possibility of creating an ultrasound scanner 1 to 3 inches in size that can be used to diagnose patients with the aid of a laptop or a mobile phone. Because of its cost and size, traditional ultrasound machinery is often not used in healthcare centers located in resource-limited environments. A prototype which was USB-based featured several probes, a 5 MHz general-purpose probe used for the kidney, liver and bladder, along with a 12 MHz ophthalmic probe used for eye examinations, and an endocavity probe used for prenatal exams, uterus and ovary scans in women and prostate exams in men [48]. Though the current cost of producing one prototype is considerable, the authors anticipate that it will be significantly lower with mass production.

In a paper by Choudhri and Radvany [49], the authors examined OsiriX Mobile, software which enables images from an MRI scan or CT scan to be downloaded onto the IOS app via a PACs server. The download happens via Wi-Fi, and to transfer the image, there is a query-retrieve protocol of the DICOM server which then pushes the images to the IOS device. These images are stored along with the patient’s name allowing for searches only by authorized personnel.

Wei et al. [50] researched the use of smart phones for fluorescent imaging of a single nanoparticle and a virus. The traditional microscope is expensive and bulky, not to mention delicate. The authors proposed to transform a smartphone into a powerful mini-microscope that can detect viruses and other microbes. They verified their theory by testing for the HCMV, a member of the herpes virus family, using the smartphone based microscope and then tested the same sample using scanning election microscopy. They encountered some challenges including a weak florescent signal, light leakage and noise detection, but they solved these by using a thin film LP filter to achieve high contrast and a high-power compact laser was installed to illuminate the sample plane in order to reduce the background noise.
Other examples of already developed devices include ‘Smart Blood Pressure’ [51] that stores information about blood pressure on a smart phone; ‘Scanadu Scout’ [52] that is a scanner and stores info on a mobile phone; ‘SpiroSmart’ [53] that monitors pulmonary ailments such as asthma, chronic obstructive pulmonary disease and cystic fibrosis; and ‘MobiUS’ [54] that is a small ultra sound connected to a smart phone.

Mobile phones as medical devices have their function in both developed and developing countries. From the perspective of medical technology, they are cheaper and smaller than existing bulky medical devices. As such they can be used in resource-limited environments to provide services unavailable otherwise. In developed countries, such devices primarily have a cost cutting function. The use of mobile phones in most of the prototypes discussed above is as data storage and for the transmission of information to remote locations. mHealth devices use WiFi for data transmission, readily available in developed countries but scarce in resource-limited settings. In such environments they can use GPRS or 3G cellular data transfers for high resolution images. The dual function of phones as a medical device plus data transmission tool makes them ideal for both locations.

The next section presents literature about technology adoption and delay tolerant networks. It starts with a table that summarizes those studies and shows how the present study fits within that area.

2.2 Literature on Technology Adoption
This section summarizes work in the technology adoption field along with several seminal papers on delay tolerant networks. Table 2.2 describes their main contribution and the relationship to this thesis. From Table 2.2, it can be seen that technology adoption is a mature area of research but very few studies are done in resource-limited settings. The main constructs of the Technology Acceptance Model (TAM) hold in almost all studies and some of the studies include additional factors.
<table>
<thead>
<tr>
<th>Paper title</th>
<th>Authors</th>
<th>Published</th>
<th>Main contribution</th>
<th>Relationship to my research</th>
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<tbody>
<tr>
<td>“A study on Singaporean women’s acceptance of using mobile phones to seek health information”</td>
<td>S. Lim et al.</td>
<td><em>International Journal of Medical Informatics</em>, 80, 2011, e189-e202</td>
<td>Applies TAM in the context of mobile health.</td>
<td>Both studies apply TAM to mobile technology and health.</td>
</tr>
<tr>
<td>“An Analysis of the Technology Acceptance Model in Understanding University Students’ Behavioral Intention to Use e-Learning”</td>
<td>S. Park</td>
<td><em>Educational Technology &amp; Society</em>, vol. 12, no 3, pp. 150–162, 2009</td>
<td>Finds that self-efficacy is the most important construct for e-learning.</td>
<td>Further narrowing of TAM to education.</td>
</tr>
<tr>
<td>“Towards an understanding of the behavioral intention to use 3G mobile value-added services”</td>
<td>Y-F Kuo, S-N Yen</td>
<td><em>Computers in Human Behavior</em>, vol. 25, pp. 103–110, 2009.</td>
<td>Finds that personal innovativeness and perceived cost influence the ease of use.</td>
<td>Similar focus on mobile technology.</td>
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</table>
of technology, intention to use and not actual use.

<table>
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<tr>
<th>&quot;Delay-tolerant networking: an approach to interplanetary internet&quot;</th>
<th>Develops architecture that encompasses three environments.</th>
<th>Seminal paper providing a basis for DNT research.</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Energy-efficient computing for wildlife tracking: Design tradeoffs and early experiences with ZebraNet”</td>
<td>Design wireless peer-to-peer network based on mobile sensors, with high latency.</td>
<td>Most quoted paper in DNT literature and as such provides background for the present study.</td>
</tr>
<tr>
<td>P. Juang, H. Oki, Y. Wang, M. Martonosi, Peh, D. Rubenstein ACM SIGPLAN Notices, vol. 37, issue 10, pp. 96-107, 2002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>“A Delay-Tolerant Network Architecture for Challenged Internets”</td>
<td>Develops network architecture for environments with long delays.</td>
<td>Both approaches are designed to deal with long delays.</td>
</tr>
<tr>
<td>K. Fall SIGCOMM’03, August 25-29, 2003, Karlsruhe, Germany, 2003 ACM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>“The challenges of disconnected delay-tolerant MANETs”</td>
<td>Designs system with sparsely populated nodes.</td>
<td>Common theme is low bandwidth for DNT network.</td>
</tr>
<tr>
<td>“Mobile Ad Hoc Networking: Milestones, Challenges, and New Research Directions”</td>
<td>Shows that mobile devices can be used as location-aware data collectors.</td>
<td>Novel approach to DTN in low-resource settings.</td>
</tr>
<tr>
<td>“Study on the Potential for Delay Tolerant Networks by health Workers in Low Resource Settings”</td>
<td>Performs a Likert scale survey about usefulness of DTN.</td>
<td>The use of surveys based on Likert scale questions.</td>
</tr>
</tbody>
</table>

Table 2 Summary of literature on Technology Adoption and Delay Tolerant Networks

The seminal work in this field has been developed by Davis in 1986. Davis [55] wrote “A Technology Acceptance Model for empirically testing new end-user information system: Theory and Results”. Technology Acceptance Model (TAM) is designed to help understand the user acceptance process, providing insight into design and implementation. Further on, it provides a theoretical basis to evaluate proposed new systems prior to implementation. It postulates that actual use is determined by attitude towards use. Attitude, in turn, is a function of two major beliefs: perceived usefulness and perceived ease of use. Usefulness is defined as a system enhancement of job performance, while ease of use means being free of physical and mental efforts. Davis tested the model in a filed survey of 100 organizational users and he validated the variables. He also performed laboratory testing on 40 MBA student subjects to test the model structure.
The theory has been applied in many fields, and in 2006, King and He [56] performed a statistical meta-analysis of TAM as applied in various fields. They used 88 published studies, and the results show TAM to be a valid and robust model that has been widely used.

While many researchers applied the TAM theory to evaluate adoption characteristics, almost all of them added new factors to the model. For example, Park [57] developed TAM for e-learning, and added subjective norm, system accessibility, e-learning self-efficacy, and behavioral intention to use e-learning. He found that TAM is a good theoretical tool to understand users’ acceptance of e-learning, and that e-learning self-efficacy was the most important construct, followed by subjective norm in explicating the causal process in the model.

Taylor and Todd [58] looked into IT usage and the role of previous experience. They compared the acceptance of experienced and inexperienced users of the system in areas such as word processing and spreadsheets. The additional factors in the model are social influence and behavioral control, and they find coefficients for all factors in their model to be significant. The most interesting finding is that communicating information to inexperienced users can have a strong effect on intentions but those intentions may not completely translate to behavior.

In 2008, a study by Kuo and Yen [59] used TAM as a foundation and incorporates personal innovativeness and perceived cost to further understand consumers’ behavioral intention to use 3G mobile value-added services. They reached the following conclusions: (1) consumer usage of current 3G value-added services remains low; (2) personal innovativeness influences the perceived ease of use; (3) perceived usefulness enhances perceive ease of use; (4) perceived usefulness has the strongest effect on consumer attitude, followed by perceived ease of use and perceived cost; and (5) the most important factor in increasing consumers’ behavioral intention to use 3G mobile value-added services is attitude.
The most relevant study to this dissertation is by Hu et al. [60] because it addresses TAM model for Tele-medicine. The authors examined the acceptance of tele-medicine technology among physicians practicing at public tertiary hospitals in Hong Kong. Their results suggest that TAM provides a reasonable depiction of physicians' intention to use tele-medicine technology. They found that perceived usefulness is a significant determinant of attitude and intention but perceived ease of use is not. That suggests that physicians are willing to put in effort and adopt technology if they find it useful in their practice.

However, TAM model is not the only model in the technology acceptance space. A paper by Sun et al. [61] “Understanding the Acceptance of Mobile Health Services: A Comparison and Integration of Alternative Models”, evaluates several models from the perspective of customers and/or patients. They design a unified model and their test results prove that the unified model outperforms the three alternative ones. The three models are TAM, the Motivation Model, and the Information System Success Model.

As found by Lim et al. [62] perceived usefulness and self-efficacy positively predict the intention to use mobile phones to seek health information. Using mobile phones to seek health information was found to be complementary to online health information seeking.

Holden and Karsh [63] studied end users’ reactions to health information technology and reviewed the application of TAM in health care. They reviewed 16 data sets analyzed in over 20 different studies of clinicians using health IT for patient care. Findings show that TAM predicts a substantial portion of the use or acceptance of health IT, but that the theory may benefit from several additions and modifications.

Jimoh et al. found that knowledge and attitude were not predictive of perceived usefulness or perceived ease of use among health workers in Nigeria [64]. Instead endemic barriers to technology are
an important addition to the TAM in low-resource settings, and that end-user preference should be considered in ICT implementation strategies in developing countries.

On the other hand, Gangon et al. examined the factors that could influence the decision of healthcare professionals to use a tele-monitoring system [65] and find that TAM is a good predictive model of healthcare professionals' intention to use tele-monitoring. However, the perception of facilitators is the most important variable to consider for increasing doctors' and nurses' intention to use the new technology.

Finally, Chuttur [66] gave an overview of TAM and summarizes the criticism regarding its theoretical assumptions, and practical effectiveness. His conclusion is that research in TAM lacks sufficient rigor and relevance that would make it a well-established theory for the science community.

This thesis investigates the attitudes of physicians and CHWs towards the use of mobile technology for healthcare applications. Since TAM has been accepted as the prevalent model in the area of technology adoption there has been little evaluation of the adoption of mobile technology in the health space in a developing country. In this thesis, TAM is evaluated in a resource-limited environment, Rwanda, with a focus on additional factors particular to mobile phones as a technology that was initially designed as a communication device but has since penetrated many aspects of everyday life as well as the work space.

In addition, this thesis discusses issues common in an unreliable telecom network that has all the characteristics of a delay-tolerant network (DTN). Such a network is concerned with interconnecting highly heterogeneous networks together even if end-to-end connectivity may not be available [67]. One reason DTN is applicable in low-resource settings is inadequate infrastructure, which includes intermittent access to the Internet. There are many rural places that are not covered by cellular phone networks. In the areas that we test our application the cellular network is available but unreliable.
There are two seminal papers on DTNs; one is 2002 by Juang et al. [68] about wildlife tracking, called ZebraNet, and the other discusses Interplanetary internet by Burleigh et al. [67]. ZebraNet researchers designed a wireless peer-to-peer network based on mobile sensors, with ad hoc routing. It is one of the first specialized protocols with high latency tolerance. They used peer-to-peer networking technique to forward data to a mobile base station without assuming the presence of widely available telecommunications support. The Interplanetary Internet [67] proposes an architecture that encompasses three environments. Each environment has a locally optimized protocol and the new architecture inserts an overlay protocol to bridge between different stacks on the boundaries. The protocol uses “least common denominator” with no elements that make it unsuitable in any networking environment. The protocol is called “Bundling” after the units of data exchanged over the network. The authors indicate that their new protocol could be implemented using TCP/IP tunnels and, as such, without changing the existing system. They suggest that supportive software is available, which allows lapses in connectivity of up to 60 minutes.

Several studies build upon the above. For example, Fall [69] proposed network architecture for environments experiencing long delays but also having end nodes with limited power or memory. To achieve interoperability, the author proposed asynchronous message forwarding, with limited expectations of end-to-end connectivity and node resources. The proposed architecture is an overlay above transport layers of the networks, and provides services such as in-network data storage and retransmission, authenticated forwarding, and grained classes of service. This study also discusses security in such networks which are relevant for medical data transport. The security that involves endpoints is undesirable for networks prone to disconnection. The author proposed an alternative security system for DTN that has verifiable access to the carriage of traffic at a particular class of service. Routers would check credentials at each DTN hop and discard the traffic if authentication fails. This approach is less susceptible to the denial of service attacks.
There are many studies about Mobile Ad Hoc Networking (MANET) and two of them are presented below. Daly and Haahr [70] discussed challenges to support communication in cases of sparsely populated nodes. They divided the challenges of Delay-Tolerant MANET in three groups. The first issue is wireless communication such as low bandwidth and bandwidth variability. The second issue is that mobility of nodes is high, resulting in disconnected network graphs. The third issue is portability where battery, processing power, and memory are limited. In wireless communications, the most interesting aspect of health data systems is asymmetric links, and they suggest several ways to reduce traffic from a low capacity link. Most of the techniques are related to reducing overheads and the size of ACK packets. Another issue they discussed that is interesting for the present application is addressing low reliability of delivery. They suggested possible solutions that include flooding, replication, hop-to-hop acknowledgment and custody transfer. The custody transfer, where a receiving node assumes custody for the eventual delivery, seems the most efficient. However, if that node unexpectedly fails the reliability would be lost.

The second study by Conti and Giordano [71] presented a new approach in the MANET research: people centric networking. In mobile multihop networking, the technology is combined with people’s behaviors and daily life activates. This has become more prevalent with the recent expansion of smart phones which act as a proxy of human behavior in the cyber world. While people move in the physical world, their mobile phones project those movements into the cyber world. The current research in people-centric networking is twofold: mobile devices are used as location-aware data collectors, and/or they are used to offer a cloud computing service. This study was published in January 2014, and the authors believe that in the near future these people-centric networks will become integrated with infrastructure-based networks.
A completely different approach regarding the potential of DTN by health workers is presented by Syed-Abdul et al. [72]. The authors interviewed health workers on the International Conference on Global Health and selected those who have health related experience in a poor connectivity context. The survey was completed using the 5-point Likert scale asking questions about potential usefulness of DTN. The response rate was 74% and 37 responses were received. The Chi squared test showed high significance for “strongly agree and agree” for the potential usefulness of DNT services, with the p-value of 0.001. They also asked about the preferred frequency of data delivery for which the responses varied considerably.

The mobile application in the field portion of the present study uses a cellular network and as such, is already more delay tolerant than if using TCP with its handshake and slow start mechanism.

In conclusion, this thesis presents an evaluation of TAM and the usability of smart phones in health data collection in limited-resource settings, and neither has been done previously.

The next section reviews the most relevant papers related to electronic data collection and usability of electronic health data.

2.3 Literature on Electronic Data Collection

2.3.1 Introduction
The first half of this section presents studies which compare paper-based systems with an electronic form of data collection, and evaluates them based on their level of consistency, completeness, time and cost. The second part of the section discusses the importance of the specific health issue to be discussed, child malnutrition, and methodology used to design child growth and development charts that measure deviation from the norm in the growth of children under the age of five. In emergency paediatric medicine, several simple models are used for a quick estimation of a child’s weight. They are also reviewed because of the parsimonious model they present.
2.3.2 Data Collection Studies

The majority of the studies found data collected with electronic tools is superior to paper-based methods. Most of the health applications studies consider feasibility and compliance to protocol or treatment. Several studies question applicability of WHO standard and develop alternative growth charts based on local children’s data using a non-parametric approach, similar to the WHO study.

Emergency medicine has its own linear and log-log models that are closer to the present approach.

<table>
<thead>
<tr>
<th>Paper title</th>
<th>Authors</th>
<th>Published</th>
<th>Main contribution</th>
<th>Relationship to my research</th>
</tr>
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<tbody>
<tr>
<td>“A Comparison of CAPI and PAPI through a Randomized Field Experiment”</td>
<td>B. Caeyers, N. Chalmers, J. De Weerdt</td>
<td>The World Bank’s multi-year research agenda in survey methodology (LSMS Phase IV), published online</td>
<td>Shows advantages of electronic data collection: elimination of data entry and consistency checks.</td>
<td>Both studies compare paper-based records with electronic records.</td>
</tr>
<tr>
<td>“Using PDA consistency checks to increase the precision of profits and sales measurement in panels”</td>
<td>M. Fafchamps, D. McKenzie, S. Quinn, C. Woodruff</td>
<td>Bread working paper no.264, June 2010.</td>
<td>Finds PDA limited for consistency checks in profit and sale measurements.</td>
<td>No improvement by electronic data collection, the opposite results.</td>
</tr>
<tr>
<td>“Malnutrition chapter by the World Bank”</td>
<td>T. Bundervoet</td>
<td>Unpublished document, based on The 2010 DHS and the 2012 Comprehensive Food Security and Vulnerability Analysis and Nutrition Survey (CFSVA)</td>
<td>Shows that probability of stunting in Rwanda peaks at the age of 12 months.</td>
<td>Both studies are completed in Rwanda, and the topic is child growth and development.</td>
</tr>
</tbody>
</table>
Table 3: Studies on electronic data collection and their relationship to the work in this thesis.

<table>
<thead>
<tr>
<th>Title</th>
<th>Method</th>
<th>Findings</th>
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</table>

In the literature on electronic data collection and the comparison with a paper-based system, the findings are encouraging that electronic data improves data quality, as measured by consistency. For example, a paper by Caeyers et al. [73] on a comparison of paper surveys, pen-and-paper interviewing (PAPI), computer surveys, and computer-assisted personal interviewing (CAPI), lists two main advantages of computer surveys: the elimination of data entry and consistency checks during interviews. The authors identify two different consistency checks: impossible and improbable data. The findings are that CAPI significantly reduces the error of inconsistencies. The authors also tested if CAPI changes the following elements: time length of survey, respondents’ perception, cost of survey, and required level of education of interviewer. They found that interview time is reduced significantly (10%), there are no differences in perception, and that the cost depends on a number of surveys collected because of the higher fixed cost of CAPI. The overall conclusion is that CAPI improves consistency, saves time and cost.
In contrast, a paper by Fafchamps et al. [74] on the use of PDA for consistency checks for profit and sale measurements, which are often noisy, finds consistency checks rather limited. In the cross section of the survey, it uses consistency checks to compare profit with sales, and prompts when the profit is missing, while in the time series portion it flags large changes from one period to the next. However, the conclusion is that the vast majority of changes are justified and volatility genuine, so it does not recommend PDAs on the basis of improvement in measurement and data consistency.

In the health field Mitchell et al. [75] test if electronic technology could improve adherence to the Integrated Management of Childhood Illness. They compared it to the current paper-based protocol in Tanzania. They randomly selected 18 clinics, collecting information during the first examination using a paper-based protocol, while the next observation was collected using electronic collection of data. The sample was 1221 children, 681 for whom information was collected via paper and 550 for whom an electronic collection was used. The authors find considerably better adherence to the protocol with electronic data collection. The conclusion is that electronic system improves completeness, defined as a reduction in missing data.

Another study [76] evaluated patient acceptance of an electronic questionnaire to collect breast cancer data in a mammography setting. The authors developed a questionnaire on a tablet computer incorporating prefilled answers and skip patterns. They tested it on 160 women, 74 using paper and 86 using a tablet, to evaluate data completeness and patient acceptance. They found it feasible (accomplished) and data quality, measured by completeness, improved.

Wilcox et al. [77] described case studies using multiple methods for primary data collection, ranging from paper to next-generation tablet computers. They performed semi-structured phone interviews and addressed issues such as workflow, implementation and security of each method. They particularly paid attention to modern methods and compared electronic health record templates which
they found difficult to use. However, they do not look at data quality, only at the usability of different tools.

The health issue for the application in this thesis is significant because Rwanda is battling child malnutrition as highlighted in research by the World Bank [78] that found that 44 percent of children under five years of age in Rwanda suffer from stunting. Stunting is defined as: “height for age below two standard deviations of the WHO Child Growth Standards median“[79], and often reflects the cumulative effects of under-nutrition or chronic malnutrition. This measure puts Rwanda on the 11th highest position in the global malnutrition league table [79]. In Rwanda, the probability of stunting for children under five increases sharply after six months of age, peaks at about twenty months and becomes relatively stable afterwards [78]. Stunting decreased by a modest four percent over the past decade, a disappointing drop given the large improvements on other development indicators.

In order to assess children’s growth, the WHO has been developing standardized growth charts since 1970. However, these charts did not adequately represent early childhood growth, and in 2006, the WHO released new growth curves. The data is a combination of longitudinal measurements of 882 children aged 0-24 months, and 6669 cross section of children aged 18-71 months old. The chart is given as a median and standard deviation estimator for each month, and is constructed based on a study that was carried out in six different countries (Brazil, Ghana, India, Norway, Oman and the USA) [79].

Soon after the newest WHO growth chart was published, Onis et al. [80] did a comparison of WHO and the Center for Disease Control (CDC) growth curves using a visual methodology. They found important differences between them, such as the CDC charts present lower rates of undernourishment and higher rates of overweight children than the WHO standards. Another approach was used in a study by Dewey et al. [81] looking at the growth of breast fed infants and constructing the growth curve
by cubic polynomial interpolation. The authors concluded that in order to follow WHO recommendations a new reference dataset is needed.

In addition, there exists some disagreement about the applicability of the WHO standard to all countries. Vignerova et al. [82] found that for Czech children, the WHO growth standard does not apply. They wrote a paper on the prevalence of wasting, defined as weight for age below two standard deviations of the WHO Child Growth Standards median, using a sample of 34000 Czech kids under five. The main difference between their study and the WHO study concerns the sample selection. The Czech study did not restrict the sample to breastfeeding mothers who do not smoke, unlike the WHO study. The authors found that many healthy children would be labeled as suffering from wasting using WHO and not local Czech standards, and recommend further evaluation of WHO growth curves before adoption.

There are many studies about the most appropriate mathematical model for describing the relationship between weight and age in children. A simple linear relationship, known as the Advanced Paediatric\(^1\) Life Support (APLS) formula [83], is used to estimate the weight of children in paediatric emergencies in order to administer correct drug dosages. APLS estimates weight in kilograms using age in years as: weight = \([\text{age} + 4] \times 2\). The simplicity of this linear formula has the advantage of being easy to calculate in emergency situations. However, as weight growth curves display evidence of nonlinearity, especially for young babies, more complex models have been developed. The Leffler formula (weight (kg) = 3(age)+7) [84] provides distinct relationships for babies below and above the age of one year. More complex models include the log-linear model of Theron (weight (kg) = \(e^{0.17 \text{age\(years\)}}+2.197\)) [85], and the non-parametric approach used by the WHO. The above formulas are interesting because they

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\(^1\) British spelling of pediatric
are unlike WHO estimate equations that could be used with different data sets, and were tested in
developing countries.

In summary, child malnutrition is a serious problem in Rwanda, and improving quality of collected
data could be essential in tracking chronic malnutrition. Mobile data collection is a way to feed timely
data into EHR and shorten the decision cycle. This thesis analyzes data from a case study in Rwanda and
shows different ways in which the electronic data is of a better quality than the current paper-based
system. This finding is important, in particular in developing countries, where data collection systems
are still rudimentary and people involved in primary data collection may not have received adequate
training. The derived model is based on a simple formula similar to the paediatric emergency medicine
models.

2.4 Sustainability and ICTD studies
The last part of this thesis addresses sustainability of ICTD projects, and Table 2.4 summarizes studies
that are related to community health interventions in developing countries. In addition, Table 2.4
presents several studies with quantitative estimates on the impact child malnutrition has on future
earnings.

<table>
<thead>
<tr>
<th>Paper title</th>
<th>Authors</th>
<th>Published</th>
<th>Main contribution</th>
<th>Relationship to my research</th>
</tr>
</thead>
<tbody>
<tr>
<td>“CommCare Evidence Base”</td>
<td>Chatfield A., Javetski G., Lesh N.</td>
<td>Dimagi web site</td>
<td>Finds that none of 26 CommCare studies showed improved health outcomes.</td>
<td>Improvement in health outcomes versus feasibility and usability.</td>
</tr>
<tr>
<td>“Using Mobile Applications for Community-based Social Support for Chronic Patients”</td>
<td>DeRenzi et al.</td>
<td>Dimagi web site</td>
<td>Finds CommCare has little effect on efficiency of home visits, produces faster reporting.</td>
<td>Looking at improvement in reporting of health indicators.</td>
</tr>
<tr>
<td>“Reliable data collection in highly disconnected environments using mobile phones”</td>
<td>DeRenzi, B., Anokwa, Y., Parikh, T., Borriello, G.</td>
<td>NSDR’07, August 27, 2007, Kyoto, Japan</td>
<td>Suggests using social links and community field workers for data collection.</td>
<td>Addresses the same DTN issue but the solution is very different.</td>
</tr>
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</table>
Table 4 Literature on ICTD and sustainability

<table>
<thead>
<tr>
<th>Title</th>
<th>Summary</th>
<th><a href="#">Source</a></th>
</tr>
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<tbody>
<tr>
<td>&quot;Research Approaches to Mobile Use in the Developing World: A Review of the Literature&quot; Jonathan Donner, Microsoft Research India, Bangalor, Published online 5/2008</td>
<td>Presents several quantitative studies that predict mobile adoption. TAM in low-resource settings.</td>
<td></td>
</tr>
<tr>
<td>&quot;m-Health Adoption and Sustainability prognosis form a Care givers’ and patients’ perspective” B. Hwabamungu, Q. Williams SAICSIT ’10, October 2010, South Africa</td>
<td>Finds that willingness and capability, along with government support, are main factors for mhealth adoption. Sustainability and adoption.</td>
<td></td>
</tr>
<tr>
<td>&quot;Discounting of life saving and other non-monetary effects” J. Keeler, S. Cretin Management Science, 1983, vol. 29, no 3</td>
<td>Proves an eternal delay if discount rate for benefits is less than for costs. Using the same discount rate for cost and benefit.</td>
<td></td>
</tr>
</tbody>
</table>

2.4.1 ICTD

There are several studies in ICTD that address mobile applications in health. An NGO, Dimagi published CommCare evidence based on mobile health systems [86]. CommCare is an open source mobile and web platform used by CHWs that has the following three critical properties: patient tracking, support
during patient sessions and ability to support multimedia. Analyzing 26 studies, the paper concludes that there is no study showing an improvement in health outcomes from adopting CommCare but there is evidence that if used correctly CommCare systems can improve community health programs.

Brian DeRenzi et al. tested Commcare with five CHWs in Dar es Salaam [87]. They found that CommCare had little effect on improving efficiency of home visits, but produced faster and easier reporting. In particular, it saved on average four hours per month on compiling reports compared to the paper system. They also discussed the advantage of Commcare being built on top of a JavaRosa software platform that is open source and has strong emphasis on standardized data representation.

Another paper by the same authors [88] addresses data reliability issues in disconnected environments. The authors leverage work completed in geographic routing and propose a best-effort “sneaker net” which uses a person, most likely to be connected in the future, to carry the data. This is a way of forwarding messages over social links which is not novel but they apply it to community field workers. Furthermore, they tested their design in Tanzania where they collected data on the real world environment and health of the local population. This paper addressed the same issue as this thesis but the solution is very different.

A great overview of how computer systems can improve healthcare delivery in the developing world was completed by Ho et al. [89] and lists the four main reasons for this improvement: 1) remote training of health workers; 2) improving supply chain of health resources; 3) integration of low-cost medical devices for usability and access in developing regions; and 4) tracking of non-communicable diseases. The paper stresses failure to scale up pilot projects and the need for applications to be able to function in unexpected operating conditions. One issue the authors mentioned related to the present study is intermittent networks and the need to select designs that deal with it.
Jonathan Donner [90] discusses the usability of TAM in ICTD and quotes several quantitative studies that have applied it to explain and predict mobile adoption in South Africa [91], Nigeria and Kenya [92]. For example, work by Biljon and Kotze [91] suggested a positive relationship between social influence and behavioral intention. These findings further validate the significance of maintaining social influence in assessing technology acceptance and particularly technologies that are prone to the public. In addition, findings from another study [92] indicate that access to mobile ICT and cultural influences on mobile ICT diffusion, strongly influence individuals’ perceptions of usefulness and ease of use of mobile ICT.

There are very few studies discussing sustainability of mHealth implementations. One, by Hwabamungu and Williams [93] divided the obstacles to mHealth adoption into objective and subjective obstacles. The objective obstacles are limitations of the current technology, specifically interoperability, and compliance to widely accepted standards and security. Subjective obstacles are reluctance of healthcare professionals to abandon traditional means of communications.

Another study by Ali and Bailur [94] considers sustainability in ICTD projects. The authors argue that sustainability is unrealistic and difficult to operationalize. Instead they recommend bricolage and improvisation.

2.4.2 Cost/benefit in health studies
There are several studies that estimate the impact of malnutrition on the economy. One of them by Alderman, Hiddinott and Kinsey [95] is concerned with long term consequences of early child malnutrition and, by following 665 children in Zimbabwe, estimates that the impact on earnings is significant, with a lower bound of 14% loss in lifetime earnings. Another study by Qureshy et al. [96] computes the cost-benefit of a stunting intervention in Indonesia. They separate the gains from improving nutrition into productivity enhancement, household savings for diarrhea cost and averted death. In this thesis, the calculation of cost-benefit to monitor children’s growth and development
adopts Alderman’s estimates for the long term savings because Zimbabwe is a comparable environment to Rwanda.

Health economics literature has been following Keeler-Cretin paradox [97] which claims that if health benefits are discontinued using rates lower than the cost, the delay will be eternal. More recent literature [98] [99] suggests using the same rate for discounting costs and benefits, interest on long-term government bonds, and cost/benefit ratio as a more robust measure.

2.5 Conclusions
In conclusion, work presented in this thesis has a multidisciplinary approach in the analysis of the implementation of smart phones in health data collection in limited-resource settings, from testing TAM and the usability of mHealth application to scalability, an appropriate business model and sustainability. Literature presented in this chapter covers comprehensive work in the field of mobile health, TAM applications, electronic data collection, ICTD studies and cost/benefit studies applied to health interventions.

2.6 References


[22] L. Osterberg, T. Blaschke. “Adherence to medication”, Massachusetts Medical Society, August 4, 2005


M. Fafchamps, D. McKenzie, S. Quinn, C. Wooddruff, “Using PDA consistency checks to increase the precision of profits and sales measurement in panels”, Bread working paper no.264, June 2010.


[93] B. Hwabamungu, Q. Williams, m-Health Adoption and Sustainability prognosis form a Care givers’ and patients’ perspective”, *SAICSIT ’10*, October 2010, South Africa.


3 Model for Mobile Data Collection

3.1 Introduction
This chapter presents the complete model for enabling data collection using mobile devices and storing them as EHRs from technical, operational, data analytics and business perspectives. The addressed problem is improving access to healthcare, and the proposed solution is an investigation of the applicability mobile technology presents for that purpose. Since in limited-resource settings, access to healthcare is often limited by a shortage of healthcare workers [1], the hypothesis is that technology could provide untrained community health workers with tools to collect important health data and bridge a gap between the underserved population and healthcare service providers. In addition, the main value of timely data availability is to shorten the decision cycle by providing decision makers with real-time information.

The technical aspect of the model relates to technology adoption in limited-resource settings and adjustment of the tools to unreliable networks involved in the data transfer. The operational perspective addresses the issue of designing a protocol for the training of CHWs that would improve the probability of adoption of those tools. As such, the protocol could be applied in other instances, in particular in other East African countries that share the same health infrastructure that relies heavily on community care. The data analytics aspect evaluates improvement in data quality when such tools are used. Finally, in the long run the solutions have to be scalable and sustainable. Because of this, it is necessary to investigate different stakeholders in the system, discover a value proposition, and find a potential business model to support a transition to new tools based on modern telecommunications.

Rwanda is often used as a ground for pilot testing because it a small country with a reasonably stable and safe environment for research. In addition, Rwanda has a fragile healthcare system with an extremely low doctor-per-patient ratio for which it is ranked 174th out of 193 countries using this measure [2]. CHWs frequently provide the backbone of its preventative and curative care, which is
typical for East African countries [3]. The following section describes in detail participants in the Rwanda health system and the information flow between CHWs and other participants in the system.

3.2 Model for electronic data collection

Electronic health records not only provide an alternative way to store medical and health data, but also suggest new methods for the collection of medical data. They have the potential to provide substantial benefits to patients, physicians, government officials and health care researchers. These systems can also improve the quality of care and patient safety [4], and EHRs make significant improvements to how information is stored, communicated and processed [5].

Data collection is essential for EHRs and the following IT devices have been previously used: Personal Digital Assistants (PDAs), tablets, portable computers, and mobile phones. The hypothesis is that data usability differs depending on the quality of data and its accessibility. The current Rwandan system for monitoring children’s growth and development is paper based. The proposed electronic system will allow collection of data in real time and have a web interface for data access and analysis. The web application will be able to display emergency cases, such as malnourished children, and at the same time track normal children’s growth and development thought time.

The following sections present participants in the Rwandan health system, communications patterns between them, and how they could improve communications with mobile data collection mechanisms.

3.2.1 Participants in Rwandan health system

Rwanda is a small country in East Africa with a population of 12 million, gross domestic product (GDP) purchasing power parity (PPP) of $1538, and a human development index (HDI) of 0.506 which is considerably low and places Rwanda in the 151st place in the world [6]. Figure 3.1 presents a map of the country with its neighbors. Rwanda has a total of four public referral hospitals that provide tertiary care,
and 42 district hospitals. In its capital, Kigali, there are only two tertiary public hospitals, one of them military. In the present study, information has been collected from the doctors in King Faisal hospital, the only private hospital in Kigali.

Figure 3.1 Map of Rwanda and its neighbors

CHWs are a major participant in the Rwandan health system that provides preventative and curative healthcare services. The CHWs are elected by their community and work as volunteers. Their activities focus mostly on children’s health, vaccinations, and nutrition, as well as community-based activities around hygiene and sanitation. They also report disease epidemics in their areas of coverage, and presently there are a total of 40,000 CHWs in Rwanda. Each sector has a CHW coordinator that they report to, and who aggregates the data on a monthly basis. Figure 3.2 illustrates participants in the Rwandan health system and the proposed information flow between them, with CHWs as an interface between the Rwandan population and health professionals, government officials and researchers interested in health data.
In the proposed model for mobile data collection the data flows from the CHWs, who collect raw data on children’s growth and development using smart phones. Smart phones are tools that enable CHWs to provide timely and accessible data. On the other side of the information flow are health professionals (physicians), and smart phones could become a tool for them to access the database and obtain information about their patients and track the progress of their treatment. Figure 3.2 presents the proposed information flow for the Rwandan health system based on the mobile data collection mechanism and, because CHWs are a focal point of the Rwandan health system, providing them with telecommunication tools could have the highest impact factor in improving the information flow in the system. At the bottom of the information stack, CHWs play an important role in providing a stepping stone for improving the quality and timeliness of health data.

3.2.2 Elements of the model
As key players within the Rwandan health system, CHWs are tasked with data collection and equipped with tools to do so electronically and store in an EHR. In this project, the data they collect is related to
children’s growth and development and nutrition. Such data can be then used to design a model for children’s development and show the influence of nutrition on growth, graphically presented in Figure 3.3. That information would be essential for prevention of malnutrition, tracking population health and diagnostics; and accessible to doctors, researchers and government officials.

![Diagram](image)

**Figure 3.3 Proposed model which links health data collection to data analytics and possible uses.**

Considering the importance of CHWs in the data collection process, it is critical to investigate factors that would allow them to adopt telecommunications technology and its tools as part of their community work. In the next section, a standard model for technology adoption is investigated and its applicability in limited-resource settings discussed.

### 3.3 Adopting IT in low-resource settings

The frequently used technology acceptance model (TAM) [7] is considered a gold standard for determining the acceptance of IT in general, and it is increasingly portrayed as fitting within the health
The basic assumption is that ‘usefulness’ and ‘ease of use’ are the two central constructs that influence attitude towards use, which then determine intention of use. TAM postulates that actual use is determined by attitude towards use. Attitude, in turn, is a function of two major beliefs: ‘perceived usefulness’ and ‘perceived ease of use’. ‘Perceived usefulness’ is defined as a perception of system enhancement of the job performance, while ‘perceived ease of use’ is a perception of physical and mental efforts. The theory has been applied in many fields, and the research shows that TAM is a valid and robust model that has been widely used [11]. However, its validity has not been extensively tested in limited-resource settings.

Figure 3.4 presents the interaction between different constructs and the system design characteristics, which are here denoted as X1, X2 and X3, in the standard TAM model.
The basic equations, which define perceived usefulness and perceived ease to use, and their impact on the attitude in a standard TAM model, are the following:

\[ USF = \sum_{i=1}^{n} x_i \beta_i + \cdots + EOU \beta_{n+1} + \varepsilon \]  
(3-1)

\[ EOU = \sum_{i=1}^{n} x_i \beta_i + \varepsilon \]  
(3-2)

\[ ATT = \beta_1 EOU + \beta_2 USF \]  
(3-3)

\[ USE = \beta_3 ATT + \varepsilon \]  
(3-4)

where:

- \( USF = \) perceived usefulness
- \( EOU = \) perceived ease of use
- \( ATT = \) attitude
- \( USE = \) actual use
- \( \beta_1, \beta_2 \) and \( \beta_3 \) are standardized partial regression coefficients
- \( x_i \) is a design feature
- \( \varepsilon \) is a random error

Figure 3.4 and Equation (3-1) - (3-4) assume that the ease of use enters the usefulness equation as a dependent variable, implying a set of structural equations. However, the underlying theory behind TAM is defined by Fishbein’s model and called attitude-toward-the-behavior [9], developed in 1967 by Fishbein, and further extended by Ajzen and Fisbein [10]. That model is represented by the following main equation:

\[ A(u, e) = w_1 P(u) + w_2 R(e) \]  
(3-5)

Attitude (A) is a function (P) that defines impact of usefulness (u), and a function (R) that defines impact of the ease of use (e). There are two weights, \( w_1 \) and \( w_2 \), and they are estimated independently.

The base of the present study is the original Fishbein model, where usefulness and ease of use are independent, and are factors that govern attitude.
In addition to above elements, Fishbein and Ajzen’s theoretical model [10] included Subjective Norm (SN) associated with a behavior related to a person’s perception about the opinion of other important to them people. However, Davis [7] did not take into account subjective norm when predicting the actual behavior of a person. The present study follows David’s model in that respect.

When validating the model, Davis developed a six-point scale measurement about people’s perception toward usefulness and the ease of use, and then matched it with self-reported usage. Prior to the test Davis gave participants one hours’ hands-on experience with the system.

Critics of TAM [11] are highlighting three important limitations of the model: 1) limitations in the testing methodology exemplified by self-reported data which is inherently unreliable; 2) limitations in the relationships between variables in the model such as looking only at voluntary and not mandatory use of technology; and 3) theoretical limitations such that intention to use does not necessary predict actual use.

Addressing the above issues, the proposed model makes observations about the actual use by CHWs, but for physicians use is self-reported. The present case study is focused on voluntary usage of the technology, and the hands-on experience provided for participants to become acquainted with the new system was nine months, considerably longer than in the study by Davis [6]. In addition, the assumption is that the usage in the pilot study would predict actual usage when the system is implemented on a larger scale.

The reasoning behind independence between usefulness and the ease of use provides motivation to evaluate the impact of previous familiarity with the device. Intrinsic dependence of usefulness on the ease of use is not obvious for devices commonly used in everyday life, and we test the validity of that hypothesis.

Chapter 2 summarizes a wider range of literature on technology adoption, but there are two studies very closely related to this thesis. One recent study that evaluates TAM as a model for testing
the adoption of tele-monitoring systems [12] by adding constructs such as ‘habits’ and ‘compatibility’, finds TAM a good predictive model of healthcare professionals who use tele-monitoring systems. Another is a paper by Gagnon et al. [13] “A model for the adoption of ICT by health workers in Africa” that evaluates TAM in Africa by adding endemic barriers to technology, including better access to technology, however it does not find these factors significant. The only significant variable in that study was ‘perceived usefulness’. Both papers give support that standard constructs in TAM are applicable in limited-resource settings and for tele-medicine, which is relevant because one of the central parts of this thesis is testing TAM in limited-resource setting and its application in mHealth.

Chapter 4 presents results from testing basic assumptions of TAM applied to physicians in a local Rwandan hospital and the community health workers participating in the case study. Both samples, physicians and CHWs, are small in size which warrants the use of the Chi squared test. Chi-square is a statistical test commonly used to compare the observed data with the expected data according to a specific hypothesis, independent of the sample size. Equation (3-6) defines the Chi squared value.

\[
Chi^2 = \sum \frac{(O - E)^2}{E}
\]  

(3-6)

where \(O\) is the observed value, and \(E\) is the expected value.

The data on actual use of technology by CHWs is not self-reported because it was possible to observe the actual use over nine months and measure it by the number of reports entered in the system. For the part of the study involving physicians in a local hospital, we had to rely on their self-reported intention to use the system, when it becomes available, because the system has not been implemented yet. The survey questions have Likert scale responses and the data is binned with four levels of response. Likert scale is the most widely used approach to scaling responses in survey research, and it is important to keep in mind the value assigned to a Likert item has no objective numerical basis.
but is a comparison between the assigned bins. A typical example of a four point Likert scale include responses such as: strongly agree, agree, neutral, and disagree.

Both groups of participants, physicians and CHWs, were given the same questions in the survey that is testing technology acceptance. It was not feasible to test the influence of prior experience with mobile technology within a group because all the physicians in the sample were already using smart phones in their private life, and none of the CHWs, before the study, were in a possession of a smart phone. Therefore, a Chi square test was performed so that physicians’ and CHWs’ answers came from a common distribution, implicitly testing the hypothesis that familiarity with the device in the private life influences adoption for work tasks.

The next section describes types of data collected during the case study and the criteria applied in the evaluation of data quality comparison between paper-based data and electronic data.

3.4 Data analysis
While the technology adoption model highlights attitudes toward the use of technology adoption, the actual use of technical tools in data collection has more concrete benefits that can be tested. This part of the model explores the advantages of electronic data collection over paper data collection and defines metrics that allow direct comparison.

CHWs from the case study collect data on children’s weight, and based on this data a local growth chart for girls and boys under five is designed. In addition, from the data collection on nutrition there is also information on the Middle Upper Arm Circumference (MUAC), a UNICEF measure for malnutrition [14]. A detailed description and analysis of data about children who are found severely malnourished (red MUAC) and chronically malnourished (yellow MUAC) will be presented in Chapter 5.

Defining data quality is the first step in the process of evaluation. Table 3.1 shows different dimensions of data quality that could potentially be enhanced by electronic methods of collection. The
dimensions are adopted from a book by Baesens’, “Analytics in a Big Data World” [15], and the first four dimensions are commonly used in data analytics research. In field studies, Baesens [15] recommends to evaluate at least one sub-dimension per category. In the present study, improving data timeliness is a critical characteristic and the last dimension is unique for digital data contribution.

<table>
<thead>
<tr>
<th>Data quality dimension</th>
<th>Sub dimension</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intrinsic</td>
<td>Accuracy</td>
<td>Data correct</td>
</tr>
<tr>
<td></td>
<td>Reputation</td>
<td>Trusted source</td>
</tr>
<tr>
<td>Contextual</td>
<td>Completeness</td>
<td>Values present</td>
</tr>
<tr>
<td>Representational</td>
<td>Interoperability</td>
<td>Language and unit correct</td>
</tr>
<tr>
<td></td>
<td>Consistency</td>
<td>Ease of understanding</td>
</tr>
<tr>
<td>Accessibility</td>
<td>Accessibility</td>
<td>Easy to retrieve</td>
</tr>
<tr>
<td></td>
<td>Security</td>
<td>Access restricted</td>
</tr>
<tr>
<td>Additional digital data</td>
<td>Feedback</td>
<td>2 way communication</td>
</tr>
<tr>
<td>timeliness capability</td>
<td>Trends</td>
<td>Visual presentation</td>
</tr>
<tr>
<td></td>
<td>Timeliness</td>
<td>Instant availability</td>
</tr>
</tbody>
</table>

Table 5 Standard dimensions to evaluated data quality along with an additional digital data dimension

The following dimensions, highlighted in red in Table 3.1, are under consideration in the present analysis:

1) Accuracy
2) Consistency
3) Accessibility
4) Feedback

From the present case study there are two data sets available: 1) paper data obtained by recording children’s weight written in the CHWs’ books and transferred to an excel spread sheet; and 2) electronically collected data of local children using a custom made smart phone application. Both data sets are described in detail in Chapter 5. Two separate comparisons were made: 1) paper data was compared to the electronic data; 2) both sets were compared to the Golden standard used in WHO growth charts. Finally, the predictive power of electronically collected local data is evaluated relative to the predictive power of the WHO model applied to the local children in Rwanda.
The first step in the methodology for comparing the above described data sets is visual inspection of the data, along with statistical analysis. The simplest assessment of the performance of a quantitative model with respect to a particular dataset is based on evaluation metrics such as the mean-squared-error (MSE), defined in Equation (3-7). In many applications, it is preferable to provide a normalized metric such as the coefficient of determination ($R^2$), which is equivalent to the square of the correlation coefficient.

\[
MSE = \frac{1}{n} \sum_{i=1}^{n} (\hat{Y} - Y)^2
\]  

(3-7)

The second step is to establish the most appropriate model for describing the datasets collected. An international standard is provided by the WHO in the form of its growth chart for children’s development. As the WHO growth charts are based on data from other countries, the intention is to understand how applicable the WHO model is for Rwandan children. In order to provide an accurate assessment of the performance of different models and different datasets, we need to avoid over-fitting problems. Unfortunately, if the same data is used for estimating the parameters of the model and also for evaluating that model, it is possible that the procedure will over-fit the data and provide overly optimistic results as far as new data is concerned.

To remedy over-fitting it is common to use cross validation, which is a model evaluation method that ensures that the evaluation is based on different data to that used to construct the model. Cross validation techniques tend to focus on randomly selected subsections of an entire data set [16]. A k-fold cross validation approach was used to calculate a sum of the MSE for each fold, divide by the number of observations, and take the square root to obtain the cross-validated standard error of estimate [16].

Another test applied to both data sets is the Jarque-Bera test, whose purpose is to test the hypothesis that a given sample of data is normally distributed with unknown mean and dispersion [17].
As a rule, this test is applied before using methods of parametric statistics which require distribution normality. The WHO model, represented by median and a standard deviation for each month, follows normal distribution so one of the methods for comparison with the WHO model is testing other models for normality. In addition, when evaluating the predictive power of field data against the WHO model, we plot cumulative density function (CDF), and perform Kolmogorov–Smirnov (K–S) test, which is one of the most useful and general nonparametric methods for comparing empirical distribution functions of two samples [18].

The last part of the model relates to the business aspect of mobile health adoption, its scalability and sustainability, and the next section lays a background for that aspect of the proposed solution. It starts with a cost/benefit analysis, introducing different elements of the cost function and estimating future benefits in the shorter and longer term.

3.5 Cost benefit analysis

3.5.1 Introduction
Cost/benefit analysis is a systematic approach in estimating the strengths and weaknesses of alternatives, with a purpose to determine if it is a sound investment or a decision. Cost/benefit literature employs two slightly different metrics. For example, Windsor et al. [19] look at cost/benefit analysis for health education of pregnant smokers and calculate the cost savings by assuming a reduction in medical expenses for underweight babies, an outcome of smoking mothers. They compute the (benefit – cost) figure to evaluate the impact of health education. O’Farrell et al. [20] use a slightly different measure; they determine the benefit-to-cost ratio, with values larger than one indicating a positive cost offset. This study uses benefit–to-cost ratio for the value metric because in a ratio form uncounted cost and benefit are more likely to cancel each other.
The next section defines cost related to the proposed system for mobile data collection of children’s health, and discusses alternatives for scaling up. The subsequent section lists benefits resulting from improved health and nutrition. In Chapter 6, there is an actual calculation of benefit-to-cost ratio along with sensitivity analysis. The last section of cost/benefit analysis discusses stakeholders in Rwanda with an interest in implementing real-time health monitoring, and data driven business models.

3.5.2 Elements of the cost function
Cost for the pilot project involved several categories: initial equipment, which was a smart phone for each CHW; training of CHWs and software development; and Internet connection for data transfer. The Tecno P3 smart phone’s price in 2013 was $100 per handset. Since then there has been a drop in price of smart phones and in 2015 there are several smart phones under $50. For example, MTN, a major Rwandan MSO, sells an entry phone for $48 [21]. When scaling up, there would be cost savings with bulk purchase, and smart phone prices could be even lower.

The pilot project was completed with 24 CHWs and in Chapter 6 there is a projection for a two-step scaling up phase involving 4000 and 40,000 CHWs in the first and second phases respectively. The largest cost was a full Internet connection, but there are several alternatives regarding Internet connection: 1) full access to the Internet which is the most expensive option; 2) alternative 1 which allows CHWs access to intra country network and communication only with each other; 3) alternative 2 requires a WiFi upload at the health centers. The second option is presently not available for purchase in Rwanda but there is an ongoing discussion with a new 4G wholesale provider to offer such a package in the near future. Alternative 3 allows CHWs to upload the data they collected during their regular visits to the health center by using WiFi. Each alternative has its own advantages and disadvantages which should be carefully weighed before making a selection.
The next section discusses the benefits of monitoring children’s growth in detail and gives justification for separating them in two groups.

### 3.5.3 Calculating benefits

Benefits are much harder to quantify than costs. If we consider only benefits of tracking and preventing malnutrition, then the benefits could be grouped into shorter-term and longer-term benefits and discounted according to the time in which they are realized.

Relatively shorter-term benefits come from the improvement in children’s health and result in lower cost of medical care, better school participation, improved cognitive development (better grades and learning), and reduction in inequality among children. They are discounted over a shorter period, e.g. 5-10 years. Longer-term benefits influence the earning power of children when they are adults, produce a healthier work force, and result in stronger economic growth of the whole country. Those benefits should be discounted for a minimum of 15-20 years. The following is a list of shorter and longer-term benefits and the appropriate discounting period.

**Benefit elements:**

**Shorter-term benefit (STB) 5-10 years**
- Better cognitive development
- Improved school participation
- Reduced cost of medical care
- Reduced inequality

**Longer-term benefit (LTB) 15-20 years**
- Demographic changes
- Higher earning power
- Healthier labor force

After adulthood, the main longer-term benefit that will be considered in this study is increased earnings. The longer-term impact of the reduction of stunting due to malnutrition on the earning power has been estimated in several other studies [22] [23], which found that earnings increase by 14% from the reduction in stunting.
For the purpose of the present study, shorter-term benefits will be included in the theoretical discussion but not calculated for Rwanda because of the lack of data to properly estimate them. There has not been a comparable study that would allow such calculations.

3.5.4 Cost benefit model
This section derives generalized equations for the total cost and total benefit discounted to the present time. The cost function is based on the case study expenses, and the total benefit on the assumptions made in the previous section.

The present value of the total cost function could be calculated based on the following equation:

\[ C_0 = E_0 + T_0 + \sum_{t=1}^{N} d^t(D_t + T_t) \]  \hspace{1cm} (3-8)

where:
\( C_0 \) – present value of the total cost
\( E_0 \) – initial equipment cost, at time zero initial equipment is assumed to have lifetime of 5 years or duration of tracking one cohort of children form age zero until the age of five
\( T_0 \) – training cost at time zero
\( T_t \) – cost for training at time t, evaluated at year’s end
\( D_t \) – cost of data transmission at time t, evaluated at year’s end
\( t \) – number of years from when the cost occurs,
\( N \) – the length of the trial is 5 years
\( d \) – discount factor, \( d = \frac{1}{1+i} \) where i is the discount rate

The present value of the total benefit per child could be calculated using the following equation:

\[ B_0 = \sum_{t=1}^{N_s} d^t S_t + \sum_{t=N_s+1}^{N_l} (d g)^t L_t \]  \hspace{1cm} (3-9)

where:
\( B_0 \) – present value of the total benefit
\( S_t \) – shorter-term benefit per child from mHealth solution at time t, evaluated at year’s end
\( L_t \) – longer-term benefit per child from mHealth solution at time t, evaluated at year’s end
\( Ns \) – number of years of the shorter term benefit per child at time \( t \), evaluated at year’s end

\( NL \) – number of years of the longer term benefit per child at time \( t \), evaluated at year’s end

\( t \) – number of years from when the benefit occurs

\( g \) – rate of economic growth

The metric for calculating the attractiveness of the solution is benefit-to-cost ratio \( (R_0) \) based on the present value of benefit divided by the present value of cost:

\[
R_0 = \left( \frac{B_0}{C_0} \right) \tag{3-10}
\]

The benefit-to-cost ratio larger than one implies positive net benefits, and, the higher the ratio, the more valuable the project.

From a business perspective, the more interesting benefits could come from the value of acquired data. The more useful data CHWs collect, the more valuable their service becomes. CHWs equipped with smart tools for electronic data collection could provide valuable information for the prevention and early detection of many community diseases.

3.5.5 Stakeholders in Rwanda
There are a number of stakeholders with different interests in mobile health application that would monitor the health of the population and provide the government of Rwanda with real time health data. The key stakeholders are: 1) the population of Rwanda; 2) the government of Rwanda; 3) neighboring countries; 4) mobile service operators that provide data service for the application; 5) various NGOs that operate in Rwanda; 6) the private sector in Rwanda; and 7) health professionals. Figure 3.5 presents different stakeholders on the influence versus interest coordinates, with the size of the bubble approximating the size of the entity.

\[ ^2 \text{ Currently in Rwanda the growth rate is 8\% per year, so } g \text{ would be 1.08.} \]
The population has a very high interest in monitoring health in real time but with very little influence. The government of Rwanda, on the other hand, has high interest and high influence.

Neighboring countries are mostly interested in disease control and detection, while NGOs may be more interested in the impact on development and could be potential funders for mHealth implementation. The private sector could benefit from implementations and provide funding, while health professionals could benefit from the innovation and influence the government into action. Finally, mobile service operators could influence the government by providing preferential pricing and corporate responsibility funding.

A benefit-to-cost ratio evaluates alternatives but the implementation of the new system would require a business model that would ensure the viability of telecom technology application for medical data collection. The next section presents different data-driven business models, and in Chapter 6 the
final analysis would lead to the outline of business alternatives that could support a switch to electronic data collection in limited-resource settings.

3.6 Data driven business model
Following the above cost-benefit analysis, there is a consideration regarding an appropriate business model, and data driven business models can be categorized as data users, data suppliers, and data facilitators [24].

Data users are organizations that use data internally either for business intelligence activities such as forecasting demand, or for predicting trends or customer churn. Data suppliers are organizations that supply data as a product for others to use. Governments are important suppliers of data because most businesses use some form of government produced data. Data facilitators are organizations that help others to exploit or analyze data [24].

If the Ministry of Health in Rwanda implements electronic data collection there could be a variety of potential customers for that data, starting with other ministries that could use such information or businesses in the healthcare sector. However, those obstacles could be practical or political, with the political barriers including protectiveness of data and reluctance to share [24].

Based on the value data offers, the government of Rwanda could follow “FREE” as a business model where customers willing to pay for data, such as insurance companies or businesses in the health field, are a source of funding for medical data collection for the whole country. Physicians, researchers and government officials in charge of public health could receive data for free because they would be subsidized by the paying customers. In addition, the population could obtain improved access to healthcare, and benefit from earlier detection of diseases, prevention, and better health outcomes.
3.7 Conclusion
The above presented model reviews technical aspects of enabling data collection with mobile devices and storing them as EHRs, along with operational, data analytics and business perspectives. In the subsequent chapters, each aspect is explained in detail and an implementation of the present case study analyzed in detail. This chapter lays the background for the interdisciplinary approach to technology adoption in limited-resource settings for medical purpose.

3.8 References


4 Technology Adoption

4.1 Introduction
This chapter discusses the adoption of telecom technology in the healthcare space, and the usability of one particular mobile application designed to collect health data. As a background for this analysis, adoption of IT in Rwanda in the general area of data collection is investigated. Specifically, different organizations in Rwanda respond to questions about the tools and methodologies they employ for collecting data.

The adoption analysis starts by investigating the attitude of physicians in a Rwandan hospital towards the use of mobile telecom technology in the healthcare space. It is postulated that adding patient consultation from a distance, using mobile technology for triage, remote diagnostics, and other services that can be offered using mobile technology, would reduce the burden currently placed on doctors. The same questions relevant for technology adoption are posed to CHWs to assess their attitude towards using mobile technology in their community health services, and compare the results between doctors and CHWs. Afterwards; the usability of smart phones is tested by putting them in the hands of CHWs to monitor children’s growth and development with a custom mobile application. The application is designed to be delay tolerant and optimized for low-resource settings. The primary goal is to determine the usability and efficacy of smart phones in health data collection, and the evaluation is carried out in an urban and a rural location in Rwanda.

4.2 Adoption of technology in health

4.2.1 Introduction
This section presents a widely accepted model for technology adoption and then investigates its applicability in limited-resource settings. Two major components from that model are evaluated in the context of Rwanda. Two groups of participants are surveyed, physicians in a local Rwandan hospital and
CHWs in a rural and urban location. The results are compared and the Chi Squared test applied to see if the answers come from the common distribution.

4.2.2 Technology Acceptance Model
In order to predict technology acceptance, the most notable application of implementation-focused research that predicts and explains reaction to the use of IT in health, the Technology Acceptance Model (TAM) [1] is adopted. TAM is a gold standard for determining the acceptance of IT in general, but is increasingly portrayed as fitting within the healthcare context [2]. However, it is not clear if TAM would capture all the unique contextual features of electronic health and a mobile phone setting. Most of the research in that space incorporates additional variables based on Bandura’s Social Cognitive Theory [3]. Examples are self-efficacy and technology anxiety [4].

Chapter 3 justifies using a modified TAM, based on an earlier version of the same theory established by M. Fishbein [5], where it is assumed that ‘perceived usefulness’ and ‘perceived ease of use’ are conditionally independent of each other and follow the equation:

\[ A(u, e) = w_1 P(u) + w_2 R(e) \]  \hspace{1cm} (4-1)

where \( A \) is attitude represented as a function of two variables:
\( u \)– usefulness
\( e \)– ease of use
and
\( w_1 \) is the weight assigned to usefulness
\( w_2 \) is the weight assigned to ease of use

Applying this model of TAM, a standard questionnaire based on a Likert scale\(^3\) of responses is designed and tested in a local Rwandan environment.

The next section presents results related to the attitude of doctors, if they are ready and willing to adopt telecom technology at their work space, and if two standard components in TAM ‘perceived

\(^3\) Likert scale is defined in Chapter 3
usefulness’ and ‘perceived ease of use’ are relevant in limited-resource settings. Data\textsuperscript{4} is collected by a survey of doctors in a hospital in Kigali, Rwanda.

4.2.3 Collecting data from doctors
The doctors who were surveyed as part of the study work at King Faisal Hospital (KFH) in Kigali which has 42 full time doctors on its staff, of whom 30 responded and met for an interview, giving a response rate of 71%. Out of the twelve remaining doctors, four refused to participate quoting their lack of interest in mHealth initiatives. The others did not respond to the invitation. These factors influence the study results, and introduce a bias because only doctors interested in the use IT in their practice took part in the interviews.

The survey was conducted through a ‘Quick Tap’ survey mobile application and doctors answered questions by simply tapping on the tablet. The application also enabled the participants to sign the consent form digitally, and collect data offline that was later synchronized with the database for analysis. The main goal in using this particular application for the survey was to provide a reference for doctors about how mobile devices can be used for data collection.

The thirty medical doctors who participated are aged between 30 and 70 years, and only five are women. About one half (46%) completed their studies in Rwanda, while the others studied either in Europe or other African countries. All the KFH departments were fully represented as shown in Figure 4.1, with percentages representing medical staff who participated in the survey. The survey was conducted on a tablet device with 30 questions related to mHealth and it took an average of 10 minutes to complete the survey.

\textsuperscript{4} Actual interviews were performed by a Rwandan Masters student who obtained local permissions for human research. This student interviewed the doctors and collected the raw data. The present study was conducted using only his summary results.
4.2.4 Results and discussion

It was difficult to test within the sample if previous experience with mobile devices would contribute to doctors’ willingness to adopt them in their medical practice because all of the doctors already use mobile phone in their daily life, and 87% of them use smart phones. Among them, 47% have already completed a consultation using a mobile device. Among the smart phone applications ‘WhatsApp’ is most commonly used application. However, voice calls and SMS are still widely used by all doctors.

Figure 4.2 presents the most common ways doctors from the survey presently seek a second opinion.
Figure 4.2 Types of applications used for seeking a section medical opinion by 30 respondents to the survey at KFH in Kigali

More than half of the doctors have chosen smart phones as their preferred device for medical applications, as shown in Figure 4.3.

Figure 4.3 Choices of preferred devices used in their profession by the survey respondents in KFH in Kigali

The medical applications that doctors would like to use mobile devices for are: triage and feedback from patients. They also believe mobile devices would improve their efficiency in receiving results from investigative labs, outpatient consultations, research and managing meetings.

The above are just personal choices of doctors in KFH but they indicate which areas the hospital should address in a custom-made application and what might help to create a standard for future medical applications.
Only two thirds of the doctors were aware of the medical devices either attached or integrated with a mobile phone or a mobile device, but almost all were willing to use them if available. When asked if they would join the team to customize medical applications for their hospital, over 90% of doctors said they would consider joining.

Among the hypotheses tested, there are two types that are important for the technology adoption analysis: 1) do doctors and CHWs find usefulness and ease of use important; 2) do both samples (doctors and CHWs) come from a common distribution. \( H_0 \) denotes the former hypothesis and \( H_{00} \) the later type.

When asked about the importance of usefulness for the adoption, 93% of interviewed doctors have chosen ‘very important’. The Null hypothesis \( (H_0) \) is that doctors do not find usefulness important and the rejection of the Null would mean that it is unlikely that such an outcome is due to chance.

\[
H_0 = \text{no relationship or doctors do not find usefulness important}
\]

The Chi square test for the above Null Hypothesis has a p-value of 0.01\(^5\) which is highly significant, so we have to reject the hypothesis, and conclude that the results are not due to chance alone. The conclusion is that the hypothesis of no relationship is rejected.

Strong attitude about user friendliness is similar. We ask if user friendliness is important factor for adoption and allow four categories, ‘strongly agree’, ‘agree’, ‘neutral’, and ‘disagree’. The Chi squared test again has a p-value of 0.01, so we have to reject the Null hypotheses that user friendliness is not important.

---

\(^5\) Chi square test typically reports p-value which represents a probability that the result is due to chance.
4.2.5 Comparing attitude of doctors and CHWs

In order to compare attitude of doctors with attitude of CHWs we interviewed 24 CHWs individually, and 19 chose usefulness to be ‘very important’ whilst 5 declared that it is ‘somewhat important’. The Chi Square test for usefulness not being important has a p-value of 0.01 which is significant. We asked about the user friendliness being an important factor for adoption and grouped answers in the same four categories as for the doctors. The Chi Squared test has the same p-value of 0.01. We have to reject the Null Hypothesis that CHWs consider both of these factors not important.

When evaluating weights of usefulness and ease of use relative to each other, both groups of participants had a question to select which of those two factors is more important. Doctors overwhelmingly chose usefulness as a more important factor. The results match a previous study in Hong Kong by Hu et al. [6] that found usefulness to have a significantly higher impact that the ease of use. KFH physicians have the same attitude; if technology is useful they are willing to adopt it even if it is difficult to use. However, CHWs found it difficult to answer the same question, and opted to put equal weight on both.

The second type of hypothesis is that previous familiarity with the mobile devices influences technology adoption, and it tests if the answers of physicians and CHWs about the usefulness came from the common distribution. The majority of the physicians (87%) and none of the CHWs interviewed had used smart phones previously, so this hypothesis would test if the familiarity with the device influences the relationship towards constructs in technology adoption. To test that hypothesis we postulate:

\[ H_{00} = \text{The two samples come from a common distribution} \]

The Chi-square test for two sample tests is based on binned data, and the binning for both data sets is the same. The assumption behind the Chi-square two-sample test is that the observed number of points in each bin (normalized for unequal sample sizes) should be close if the two data samples come
from a common distribution. When testing the two sample groups, CHWs and doctors, the test at the p value of 0.01 is significant and the Null Hypothesis that both physicians and CHWs come from the common distribution is rejected. The same holds for the user friendly attitude. Table 4.1 presents a summary of Chi Squared tests.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Hypothesis</th>
<th>Physicians</th>
<th>CHWs</th>
<th>CHWs and Physicians come from the same distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usefulness</td>
<td>Not important</td>
<td>Reject p=0.01</td>
<td>Reject p=0.01</td>
<td>Reject p=0.01</td>
</tr>
<tr>
<td>Ease of use</td>
<td>Not important</td>
<td>Reject p=0.01</td>
<td>Reject p=0.01</td>
<td>Reject p=0.01</td>
</tr>
</tbody>
</table>

Table 4.1 Chi Square test summary for importance of usefulness and ease of use, and if CHW and physicians came from the common distribution.

4.2.6 Conclusions
The above presented data shows that TAM model holds in low-resource settings and that both groups of participants find major components, usefulness and ease of use, very important for adoption. However, we could not find evidence that the responses from both groups, doctors and CHWs, come from a common distribution. That is not sufficient to claim that previous experience influences attitudes towards adoption, just that in this particular case the two samples do not follow the same distribution, and thus it can’t be claimed that previous experience is unimportant.

The next section presents the status of Rwanda in a general data collection field, and tools and methodologies presently employed by Rwandan organizations. The goal is to investigate if presently Rwanda is using a paper-based system for data collection or electronic tools to collect and store data.
4.3  Electronic data collection

4.3.1  Introduction
Primary data collection is a principal component not only in health but also in many research studies, business and government decisions, and development evaluations. In a fast paced world with the ever growing role of information technology, there is a movement to make transition from a standard paper-based data collection method to electronic and technology enhanced process. If the goal is to have evidence-based, adaptive and agile decision making and to transform the way development is currently practiced, real-time data is an imperative.

In particular, developing countries are struggling with delay in relevant data, problems in access, and human resistance. In this section, we present findings about the state of IT adoption for data collection in Rwanda and the attitude of organizations about the transition to digital data collection. To that end, we performed a qualitative study by interviewing representatives of different organizations in Rwanda about issues in data collection, evaluating challenges they face, and asking about ways in which improvements might be made.

4.3.2  Methodology
To determine what constitutes best practices in Rwanda, interviews are conducted of representatives from twelve different institutions in the country. Most often representatives held positions as monitoring and evaluation officers and/or data managers, and in some cases we spoke to the owner of the company or a manger of a data collection unit. The participants came from four international NGOs, three local NGOs, three private companies and two government institutions. Table 4.2 is a summary of the data collection mechanisms across the different types of organizations.
<table>
<thead>
<tr>
<th>Type of organization</th>
<th>Number of organizations</th>
<th>Data collection mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>International NGO</td>
<td>4</td>
<td>3 use paper-based system and 1 uses mobile phones and tablets</td>
</tr>
<tr>
<td>Local NGO</td>
<td>3</td>
<td>Paper-based system</td>
</tr>
<tr>
<td>Private company</td>
<td>3 (2 local and 1 foreign)</td>
<td>Local company uses paper-based system. Foreign uses tablets.</td>
</tr>
<tr>
<td>Government institution</td>
<td>2</td>
<td>Both use paper-based system</td>
</tr>
</tbody>
</table>

Table 4.2 Types of organizations surveyed in Rwanda and their data collection mechanisms

The main points of the interview have been classified into three categories: strategy in data collection and tools used, data quality assurance challenges, and room for improvement. Two distinct approaches in data collection emerged:

1) General strategy driven by cost effectiveness and quality assurance
2) Donor or client driven strategy that changes with each project

Only two organizations are able to implement the general strategy: one private company and one international NGO. As a consequence they moved from paper-based methods to electronic methods; with the outcome of timely and easy to share data. Both organizations used mobile phones and tablets to collect data, and applications for those tools were open source or commercial, depending on the complexity of the project. The data storage was on a local server in both cases. The main driver for this approach was a need for higher data quality and cost reduction because it eliminates the data entry step. This is relevant as, according to the participants in this survey, the majority of errors happen at the data entry stage.

The donor or client based strategy is defined as when an institution does not have a specific and permanent methodology for collecting data. They perform activities based on the requirements from a client or donor. This approach does not allow the organization to be innovative nor to develop a unified
strategy in their data collection process. Many donors request a specific methodology and do not allow the organization any choice in the methodology used. Participants from that group, ten organizations, did not perform cost/benefits analysis for electronic data collection system.

For them data quality is addressed at two different stages; during data field collection and during the data entry process. Those organizations that still collect data using paper-based systems have developed processes to ensure data quality, and they are presented in Table 4.3.

<table>
<thead>
<tr>
<th>Field collection</th>
<th>Field supervision</th>
<th>Each team is assigned one or two supervisors. The supervisor reviews data while on the field and identifies any data quality issues in the early stages.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field briefing sessions</td>
<td>At the end of each day, the team meets and reviews data collection figures and issues are resolved the next day while still in the field.</td>
<td></td>
</tr>
<tr>
<td>Data entry</td>
<td>Double entry</td>
<td>Two independent data entry assistants enter data into an electronic format or data repository, and results are compared for quality improvement and to eliminate human errors.</td>
</tr>
<tr>
<td>Cleaning</td>
<td>During and after the data entry phase, different institutions administer data quality checks to identify data quality issues which might have escaped during previous quality checks. The most popular software for that function are: SPSS and STATA.</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3 Strategies to ensure data quality while collecting data using paper, identified during interviews with Rwandan NGOs and businesses.

In electronic data collection, data assurance is maintained from the early stages of the survey or questionnaire design. The electronic collection process enables them to: automate skips; validate data rules on the variable; observe warnings for unlikely values; and undertake cross checks based on the values of different variables. This prevents a substantial number of errors. At the cleaning stage, the user deals with some uncontrollable errors that cannot be detected with technology. When using this method, there is no need to perform data entry as all collected data is in a format which can be shared in a timely manner, both offline and online. Most participants of the survey agree that technology would help improve quality and availability of data. However, participants from NGOs and the private sector were skeptical that the Rwandan population would take electronic methods seriously, implying their hesitations towards technological applications in Rwanda. As a consequence, ten out of twelve
organizations still use paper-based surveys, and only one private company and one international NGO have switched to tablets and mobile phones as tools in field data collection. The participant for the NGO that already uses electronic tools suggested developing an automated process of data screening and updates.

Lack of immediate and real time feedback on the data collection progress is another challenge. Institutions have to wait in order to perform any analysis with the collected data until it is entered into the electronic form. Once data is collected, some institutions are not able to establish shared and well controlled repositories for archiving and sharing their data. Even the larger NGOs from our sample do not have established processes for data sharing, and do not have a central data repository.

Every institution would prefer data available in real time, but in Rwanda the use of electronic tools is still not widely practiced, even by the larger international NGOs or government offices. One of the key reasons for this is inadequate ICT literacy. In early 2015 the Rwandan Ministry of Youth and ICT stated that only 3.3% of population has adequate ICT literacy [7], and that they are planning to launch the “National ICT Literacy and Awareness Campaign in Rwanda” [8], with the plan to increase the literacy rate to 50% by 2018. The goal of 50% is over optimistic but the campaign will improve the perception of the population towards technology, and contribute to the adoption of electronic data collection in Rwanda.

4.3.3 Technology description
In this section the term technology is used loosely, and it means Information and Communication Technology (ICT), with its forms such as mobile and cellular, as well as with long distance fiber optic options. The tools used are mobile phones, tablets and portable computers. Electronic data collection describes the use computerized forms and electronic tools, while standard systems are paper-based forms, surveys, questionnaire, and in the subsequent case study, notebooks for entering medical
information. Telecommunications services are voice, text messages (SMS) and data connections, such as General Packet Radio Service (GPRS) or 3G connections.

4.3.4 Business benefits
An effective business process would benefit from data collection based on technology. The current Rwandan ICT profile, especially mobile and wireless based solution penetrations, are enabling this process. At the end of 2014, Rwanda had reached 70% of mobile-cellular phone penetration and a countrywide internet penetration of 27% [9]. Consequently, Rwandan businesses and NGOs could take the initiative by implementing technology based solutions and improving data quality and timeliness.

Initial investment in equipment for electronic data collection is surprisingly low to deter even a small organization. Most popular tools for electronic data collection are tablets which cost between $50-100. Another example is the present case study where an investment would mean purchasing smart phones which have recently become available for between $25 and $50 per set. CHWs working for the Health Ministry of Rwanda could also perform data collection for other ministries. Once trained on the use of equipment they could send invaluable information instantly to many portals of open data and be agents of change for the fast growing economy of East Africa. Chapter 6 discusses cost/benefit analysis of the switch form paper to electronic data collection methodology.

Using technology in data collection presents several benefits to all stakeholders, and Table 4.4 contains a non-exclusive list.

**Process automation:** The whole process could be automated and remotely controlled. This would allow real time monitoring and feedback.

**Increase in quality:** Data validation rules, skips, logic controls and environmental conditions can be controlled and enforced in order to collect relevant and accurate data.

**Data sharing:** Adopting technology in data collection allows central storage, replication, and sharing. Data could be adequately protected with fire walls and anti-intrusion systems.
**Manageability:** During data collection, any change to the protocol or questionnaire could be instant without the costly logistics of paper printing, storing or distributing.

**Improvement in logistics:** In the long term, technology does not require expensive logistics compared to present existing methodologies.

| Table 4.4 Benefits from technology in data collection identified during interviews with Rwandan NGOs and businesses |

4.3.5 Conclusions
The survey of Rwandan businesses, government organizations and NGOs presents a picture of the current state of adoption of electronic and technology enhanced data collection process. It is not surprising that almost every institution would prefer data available in real time; however, not many are contemplating adopting electronic tools in order to improve quality and cost. The main reason they seem reluctant is their view about the perception that the Rwandan population has towards ICT tools.

4.4 Usability of the mobile application for CHWs

4.4.1 Introduction
Usability is another topic of this research and it involves the implementation of a particular mobile application for data collection. Three aspects of usability are measured: effectiveness, efficiency, and satisfaction. In addition, one other aspect of usability is that CHWs operate in unreliable network conditions. To address that issue a delay tolerant application (DTN) is developed. We then follow 24 CHWs for nine months and observe their use of the application as well as any problems they face relating to its use. This section presents the importance of DTN design and the results from the field study. The next section discusses DTN design and reasons for its implementation.

4.4.2 Delay tolerant application
In limited-resource settings there are common issues relating to an unreliable telecom network that has all the characteristics of delay tolerant network (DTN). Such a network is concerned with interconnecting highly heterogeneous networks together even if end-to-end connectivity may not be available [10]. One reason DTN is applicable in low-resource settings is inadequate infrastructure, which includes intermittent access to the Internet. There are many rural places that are not covered by cellular
phone networks. In the areas that the application was tested the cellular network is available but unreliable. Therefore, this study explores ways to adapt the application for medical data collection to perform in such conditions. The delay tolerant application used for the study sends the collected data when it senses a connection to the network and meanwhile it stores it on the device. Figure 4.4 presents the logic in functioning of the DNT aspect of the application.

![Diagram](Image)

**Figure 4.4. Algorithm for collecting and transporting data from the mobile application to the server during the field study**

In “A delay-tolerant network architecture for challenged internets” K. Fall [11] lists high latency and low data rates as one of the path and link characteristics. For our application the data rates are small, in kilo bites, and allowed latencies large, in hours. In addition, the link could be designed as largely asymmetric until we incorporate feedback mechanisms that give real-time responses to CHWs. The mobile application we are testing uses the cellular network, and, as such, is already more delay tolerant than if using TCP with its handshake and slow start mechanism.

To justify a DNT design we obtained statistics about the Quality of Service (QoS), a measure of reliability of mobile service, by MTN, Rwandan largest service provider, and the numbers are reported by the Rwandan Utilities Regulatory Authority (RURA) [12]. In the city of Kigali, call setup success is 92.6% which is lower than MTN license obligation [13], and the call drop rate is 0.63%. Interestingly, the
Northern and Eastern provinces, which are largely rural, are much better at 99% and 98% success rates, respectively. These numbers are optimistic relative to the everyday experiences in Kigali where it often takes two to three attempts to establish a cellular phone call [14].

### 4.4.3 Usability

In standard usability models the measure of usability is typically expressed in terms of three attributes: effectiveness, efficiency and satisfaction [15]. Those three attributes were measured and evaluated during the field study in the following ways:

1) Effectiveness means producing the expected result or the ability of the user to complete a task in a specified context. The context of interest is limited-resource setting and users with no previous experience with the equipment. The results were measured in terms of data entered as defined by the numbers of children registered in the system.

2) Efficiency means performing a function in a timely manner with little effort, or user ability to complete the task with speed and accuracy. The results were measured by the time it took to train the users and make the system functional, as well as the number of problems encountered before completing the task.

3) Satisfaction means the perceived level of comfort; and it is evaluated during the exit interviews as participants were asked how easy is to use the application and the overall new system.

### 4.4.4 Trainings of CHWs

The field project lasted from March to December of 2014, and included eight regular trainings of CHWs, with each training session lasting on average four hours. The trainings were held on two different locations, Remera (urban) and Bumbogo (rural) health center.

The total number of 24 CHWs was involved in the project, 12 at each location. The first meeting included the dissemination of smart phones and an introductory lecture on how to use mobile data services.
The application was installed on a Tecno P3 smart phone, with the following technical specifications:

1. Available storage:
   a. External storage SD card: 7.30GB
   b. Internal storage: 100MB
   c. SIM Dual mini SIM

2. Operating system specifications:
   a. Android version: 2.3.5 Gingerbread
   b. Kernel version: 2.6.38.6-perf
   c. Processors: 800 MHz dual-core CPU
   d. RAM: 512 MB

The first two trainings concentrated on instructions of how to use a smart phone and the Internet. In addition, at the second meeting a representative from MTN (local service provider for this project) explained how to use the package purchased for the CHWs to access the Internet.

The design interface of the application mimicked a paper form for entering a child’s weight currently in use by the same CHWs. The group in Remera (urban) did not have as many problems learning how to use a smart phone even though all but one CHW had never used it before. Under supervision, they opened Gmail accounts and we generated a WhatsApp group with a local Rwandan student as an administrator, to provide help with technical problems. The group in Bumbogo (rural) was difficult to train and had many more problems which required an extra training session to make the application functional. Some of the planned activities, such as establishing a WhatsApp group, were not possible because the network kept crashing while opening Gmail accounts. In addition, Bumbogo users were not interested in communicating via a chat application and preferred voice calls.

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6 WhatsApp is a popular chat application in Africa and other developing countries.
The mHealth application was designed in two languages: English and Kinyarwanda (the local language used in Rwanda). Figure 4.5 contains snap shots of the application interface for the weight collection, while Figure 4.6 presents the nutritional survey interface. The nutritional survey mimicked a similar survey completed in 2004 in Rwanda [17], and is explained in detail in the later part of this section. In the nutritional survey all the questions were menu driven with drop down choices, check boxes, or ‘yes’ or ‘no’ answers.

Figure 4.4 Interface for weight and MUAC collection from children in the field study
Some of the common problems and solutions during the project were the following:

1. The mHealth application had somehow disappeared from the phone and we had to reinstall it
2. CHWs forgot their password and we had to restart the application
3. The phone malfunctioned and often just restarting it helped
4. Data did not synchronize with the server which was an issue on our side

The data was stored on the campus server which had a public IP and a private (from the campus) IP address. The CHW coordinator and e-health coordinator from the Rwandan Ministry of Health had the public access to the server.

During the nine month period CHWs collected the data on weight for 992 girls and 862 boys under the age of five. They also registered MUAC (middle upper arm circumference), a UNICEF measure for malnutrition [16], and performed a survey on nutrition of the same children. The nutritional survey was divided into 3 subsections: feeding practice, sanitation and food diversity. The food diversity scoring divided food into seven groups, based on their importance for child’s growth and development, and
each child obtained a score 0-7 depending on how many food groups he/she consumes. The food groups are the following:

- Protein
- Carbohydrates
- Vitamin A rich food
- Vegetables
- Fruit
- Oil and fat
- Milk and milk products

While monitoring initial results, we discovered that CHWs were not doing the survey correctly when it came to the diversity of diet. More than the half of children was receiving a score indicating they consume all seven food groups. For example, we noted one entry which stated a one year old child nursing four times a day, and consuming all seven food groups, including beef, eggs and cheese.

A separate meeting was organized to discuss the data from the nutritional survey in an attempt to resolve the issue. The coordinator of CHWs told us that the nutritional survey is new for CHWs and that they do not understand the purpose of it, and most likely the answers to the questions were fabricated. At the meeting CHWs told us that they did not understand the survey and have chosen the answers randomly. They assured us that they will correct the issue. In the later months the issue was resolved and the results from the nutrition survey is presented in the next chapter.

Other questions in the survey have reasonable and expected answers. For example, the number of daily feeds for a child is 2.8 times a day, higher than that found in the study 12 years ago [17] which reported 2.1 feedings a day.

In August 2014, we followed five CHWs on their home visits. Challenges realized during those home visits included:

1. All CHWs are still running an older version of the application (1.2 and not 1.3)
2. They do their CHW tasks after their regular working hours, exhausted and prone to errors.
3. Two out of five CHWs had technical issues with the phone or applications and did not report them to us or their coordinator.
4. Some of CHWs collect the information about children’s weight initially on paper and then transfer this to the phone application after they return home. This way they do not utilize the real time error detection features of the mobile application.

At the last meeting in late December, we gave a presentation of the findings to CHWs and performed exit interviews to obtain their feedback. We asked them about problems they encountered and recommendations for improvement. The phones they used for the data collection were left with CHWs so that they continue to use telecomm tools and stay informed.

The main points from exit interviews can be summarized as following:

- The biggest problems in the adoption of the new tool were becoming accustomed to the device, typing on the small keyboard, and using the touch screen. However, these issues were twice as common in the rural as in the urban location.
- For the CHWs the biggest advantages of the new system were the ability to access the previous entries, and the fact that all the information was accessible from one small device they carry in their pocket. All of them said that it made their job easier.
- The CHWs from the urban location took several weeks to get used to it, while in the rural location it took several months.
- All of the CHWs agreed that having real time feedback would be very useful to them and to the parents of the child.

When asked about the largest benefit of the study they most frequently quoted: learning to use a new device, and having access to the information related to their work and in general.
4.4.5 Lessons learned and recommendations

The application was well received and we only lost two participants in nine months, both because of equipment loss. The following lessons are generalizations obtained from working nine months with 24 CHWs.

1. CHWs are comfortable with the part of the application that is replicating their work in collecting weight on children under five. They were able to use it with minimum training. However, they had lots of problems with the survey part which is new to them. It was difficult to use a new technical tool and learn a new task at the same time.

2. Many CHWs have never used smartphones before but we were able to teach them that skill in two meetings. The settings on the phone are in English and they were also able to adjust to that. Once they learnt how to use a smartphone, learning how to use the application was relatively easy.

3. CHWs are very interested to learn about the whole system and purpose of the study. They all expressed interest in knowing the ultimate goals and had many suggestions on how to improve the system.

4. While following them on home visits we found out that they are often tired after finishing their regular jobs and have difficulty concentrating on the community work tasks. They often forget to bring the phone, especially if they go to visit families immediately after work.

5. Within six months of the study, there was attrition and in this case the loss of equipment. The equipment was not replaced since the study is nearing its completion. We removed the relevant participants from the study.

Table 4.5 summarizes observed problems and feedback from the exit interviews.

<table>
<thead>
<tr>
<th>Common observed problems</th>
<th>Minimal problems with the part of the application that replicates familiar work such as weight and MUAC collection.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Significant problems with the survey part that is a new methodology. It was difficult to use a new technical tool and learn a new task at the same time.</td>
</tr>
<tr>
<td></td>
<td>The settings on the phone are in English (most CHWs do not speak English)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Feedback at exit interviews</th>
<th>The biggest challenge was becoming accustomed to the device itself. In the urban location, this took several weeks, in the rural location it took several months.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>The biggest advantage of the new system is access to previous entries, and capability to access information from a device you can carry in a pocket</td>
</tr>
</tbody>
</table>
Real time feedback on child development would be very useful to CHWs and to the parents of the child.

The largest benefit of the study is learning to use a new device, and having access to the information related to their work and in general.

Table 4.5 Problems and feedback identified during interviews with CHWs during the field study

| 4.4.6 Conclusions and scaling up |
The results showing the measurement of the three attributes can be summarized as following:

1) The measure of effectiveness in terms of numbers of children registered in the system is 1700 children registered in the system for the period of nine months.

2) Efficiency was measured in training time to make the system functional, as well as the number of problems encountered before completing the task. It took total of three trainings (four hours each) to make the system functional.

3) Satisfaction means the perceived level of comfort, and all the users were extremely satisfied with the application and the new system of reporting.

This project was a feasibility study and in order to scale up the system to the whole country there are several considerations. The data package for the 24 CHWs was expensive and scaling it up would be expensive. Table 4.6 presents three scenarios in implementing the project to the whole country and two phases. The alternatives are: 1) full access to the Internet; 2) internal networking where CHWs and the Ministry of Health are connected; and 3) WiFi data transfer at the health centers. The second and the third alternative are considerably less costly and would enable the CHWs to perform data collection task. However, it would limit their access to other information and the device (smart phone) would lose its multi-functionality.

<table>
<thead>
<tr>
<th>Type of cost</th>
<th>24 CHWs ($100/phone)</th>
<th>4000 CHWs ($50/phone)</th>
<th>40,000 CHWs ($25/phone)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment</td>
<td>2,400</td>
<td>200,000</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Initial training and software development</td>
<td>384</td>
<td>64,000</td>
<td>640,000</td>
</tr>
<tr>
<td>Ongoing training</td>
<td>120</td>
<td>20,000</td>
<td>200,000</td>
</tr>
<tr>
<td>Full Internet connection</td>
<td>360</td>
<td>60,000</td>
<td>600,000</td>
</tr>
<tr>
<td>Alternative 1: internal network within the country</td>
<td>240</td>
<td>40,000</td>
<td>400,000</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>-----</td>
<td>--------</td>
<td>---------</td>
</tr>
<tr>
<td>Alternative 2: WiFi at the health center</td>
<td>48</td>
<td>8,000</td>
<td>80,000</td>
</tr>
<tr>
<td>Total cost</td>
<td>3,264</td>
<td>3144</td>
<td>344,000</td>
</tr>
</tbody>
</table>

Table 4.6 Scaling up estimates for mobile data collection cost based on 3 different alternatives for data transfer.

4.5 Conclusions

Evaluation of TAM in a limited-resource setting started with inquiring about the attitudes of physicians and then CHWs towards mobile technology in the health space. Both surveys suggest that physicians and CHWs are willing to adopt technology if they find it useful in their practice. Both groups find usefulness and ease of use important, and the weights of these two components are skewed towards usefulness for the physicians and are equal for the CHWs. Physicians are willing and eager to improve efficiency in receiving results from investigative labs, outpatient consultations, research and for managing meetings. CHWs are more inclined to adopt new technology if the task is familiar and they are changing only an implementation tool. They find it difficult to use a new tool and also learn a new methodology. However, they found mobile technology appealing in providing real-time feedback and access to previously collected data.

General awareness and adoption of IT for data collection in Rwanda is low. A few foreign NGOs and some private companies are already using tablets and mobile phones to collect data for their own use and for organizations that base their decisions on primary data. However, most NGOs and private organizations are still reluctant to change because of the low ICT awareness of Rwandan population, despite understanding the value of timely and relevant data.

CHWs reacted positively towards a custom mobile application and found its usability high to stay engaged for nine months. The added benefit of having access to the Internet kept them interested in the
system, and it took between several weeks for the urban and several months for the rural group to completely adjust to the new system.

Usability of the custom mobile application showed effectiveness with close to 2000 children recorded in the system. As a measure of efficiency the time to train users with no prior experience was three trainings, four hours each. Satisfaction of all 24 users was extremely high.

The lessons learned and the scaling up estimates based on this pilot project provide policy implications for the country of Rwanda and East African region, where most countries base their health system on community health workers. In addition, CHWs are the backbone of some Asian countries, such as India, Pakistan and Bangladesh, where the proposed mobile data collection could be useful as well.

In conclusion, Rwandan doctors and CHWs who were participants of this study understand the benefits mobile technology can provide to their practice and both the perceived usefulness and ease of use as important factors. They are eager to adopt technology that they use in everyday life and perceive it as a way to reduce a burden they experience in a limited-resource setting. During the field study, CHWs were very satisfied with the mobile application and were effective in data collection, while the scaling up estimates are encouraging for developing countries like Rwanda.
4.6 References


5 Data Quality

5.1 Introduction
In this chapter, a hypothesis is tested that electronic data collected by CHWs is superior in quality than data from a standard paper-based system. The first step is to compare the quality of the electronic and paper-based data collection approaches. Along with visual inspection of the data, statistical analyses were also used to quantify the quality. The second step is to establish the most appropriate model for describing the datasets collected. Both datasets, electronic and paper-based, are compared to the Golden standard which is provided by the WHO growth chart on children’s development. The purpose of this chapter is to visually demonstrate and quantify the differences in data quality, and test whether or not electronic data has higher usability than paper data, defined as better satisfying intended use of the data.

One limitation of this study is that a systematic error could be present in either of the collection mechanisms and that there could be a bias that introduces a systematic error. When switching between methods it was not possible to hold all other (relevant) factors constant in order to establish a causal relationship. This result is due to the nature of data collection in the real world; rarely it’s possible to have a controlled experiment that allows uncovering causality [1]. In this case study the same set of CHWs was collecting the data but the paper records were collected in the first half of 2013 and the electronic in the second half of that year. There could have been a number of unforeseen elements that changed which have not been measured.

The review of literature chapter, Chapter 2, presents previous work on electronic data collection attributes, research on children’s growth charts and the health status of Rwandan children, and several simple models for prediction of child’s weight in emergency pediatrics medicine. This chapter outlines a general framework for comparing data quality using electronic tools, such as modern telecommunications equipment, and paper-based collection.
The next section describes different data sets collected by CHWs, data from a nutrition survey, and data tracking weight and middle upper arm circumference (MUAC) of Rwandan children under five.

5.2 Types of data collected by CHWs

5.2.1 Introduction

CHWs collected two different datasets for this project. Once a month CHW visits a family and measures a child’s weight in order to track the child’s development. For the purpose of this project they recorded this information, along with the age of the child and parent’s information, using a smart phone application which synchronized with our database. A standard measure of the appropriate weight for children under five is based on UNICEF/WHO standard called MUAC and it is a simple band with three different colors [2]. CHWs routinely collect both of these metrics for all children in their village.

The second type of data comes from a nutritional survey that was incorporated in the mobile application. At the beginning of the project CHWs asked parents questions about the types of food they feed their children and the frequency of feeding. The survey was organized so that the parents had to answer yes/no, drop menu and multiple choice questions. Food was divided into seven food groups important for children’s growth and development, and after the survey each child received a nutrition score ranging from 0-7 depending on how many food groups she/he consumes.

5.2.2 Data from the nutrition survey

CHWs had many problems during the administration of the nutrition survey. Parent’s answers were not realistic and CHWs did not know how to deal with this issue. They allowed parents to give answers such that a four months old baby is fed every single food group including beef and milk. After several meeting with CHWs, where we discussed those problems, they were able to collect reasonable data. However, the reliability of the survey is still questionable, in particular considering cultural obstacles. Figure 5.1
shows a snapshot from the web application of a nutrition score distribution. At the end of the project we calculated that the average nutrition score for Rwandan children under five is 4.1.

![Figure 5.1 Distribution of the nutrition score for Rwandan children under five ranging from 1-7](image)

Ten years ago a different study [3] evaluated the nutritional status of children under five in 11 countries, among them Rwanda. Table 5.1 has a comparison of this study with the study in 2004.

<table>
<thead>
<tr>
<th>Comparison criteria</th>
<th>Study in 2004</th>
<th>Present study (2014)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food diversity score</td>
<td>2.9 out of 7</td>
<td>4.1 out of 7</td>
</tr>
<tr>
<td>Frequency of feeding</td>
<td>2.1 times per day</td>
<td>2.8 times per day</td>
</tr>
</tbody>
</table>

Table 5.1 Comparison of food diversity and frequency of feeding between present study and a study from 2004.

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7 As described in ref [3]
5.2.3 Data on MUAC and weight

MUAC and child weight are metrics CHWs routinely collect and they have a better understanding of their meanings. They are also simpler to measure and do not require feedback from families. CHWs encountered no difficulties in collecting those quantities.

MUAC is a measure of malnutrition and it is defined as the following:

- Acute malnutrition is defined by MUAC < 110 mm and is shown by a red color band, with a recommendation that the child should be immediately referred for treatment.
- A green color band indicates an appropriate nutritional status and MUAC > 135 mm.
- A yellow color band is 110 mm < MUAC < 135 mm, and it indicates that the child is at risk and should be counseled and followed-up.

Figure 5.2 is a snapshot of a web application representing frequency of MUAC in our sample of children under five. There were very few children with yellow and red MUAC, in particular in comparison to published Rwandan statistics by the World Bank [4].
Present study sample had only 33 children with red MUAC kids, with about half of them boys and half girls. Yellow MUAC was detected for only 14 children.

Tracking weight of children under five is a standard procedure and in 2006 WHO published an empirical non-parametric model based on six countries around the world. Those countries were Brazil, Ghana, India, Norway, Oman and the USA. The only country from Africa, where the survey was conducted, was Ghana, which is 71st on the rating for the risk of malnutrition, where 10.5 in 100,000 children die because of malnutrition [5]. In comparison, Rwanda ranks 18th on the list of countries with high malnutrition, with 23.6 in 100,000 children dying because of malnutrition [5], which is more than twice that of Ghana. Another country in the WHO sample with high malnutrition is India, but its rate is below Ghana at 4.39 in 100,000 children [5]. In other words, children in Rwanda have a considerably higher rate of malnutrition than in all the countries from the WHO sample. This leads us to suspect that WHO growth chart is a model with low predictive power for Rwandan children.
The next section discusses methodology used in assessing data quality attributes. It details assessment tools applied in quantifying the quality characteristics, as well as the data quality dimensions.

5.3 Methodology

5.3.1 Quantitative assessment
The simplest assessment of the performance of a quantitative model with respect to a particular dataset is based on evaluation metrics such as the mean-squared-error (MSE) [6]. MSE is defined as following:

\[ MSE = \frac{1}{n} \sum_{t=1}^{n} (A_t - F_t)^2 \]  \hspace{1cm} (5-1)

where \( A_t \) is the actual value and \( F_t \) is the forecast value.

Another measure is Mean Absolute Percentage Error (MAPE) which is defined as following:

\[ MAPE = \frac{1}{n} \sum_{t=1}^{n} \left| \frac{A_t - F_t}{A_t} \right| \]  \hspace{1cm} (5-2)

\( A_t \) represents the actual value and \( F_t \) is the forecast value.

Both measures were used in quantifying the quality of the data. The advantage of MSE is that it uses the same units as the assessed variable, in this case weight of child in kilograms. In combination with MAPE which produces the percentage error, both metrics provide the basis for the quality of model predictive power.

The first step is to compare the quality of the electronic and paper-based data collection approaches. Along with visual inspection of the data, statistical analyses were also used to quantify the quality. We compared a number of parsimonious parametric models for describing the relationship between weight and age and found that the most appropriate model structure was of the form,
log(weight) = a + b log(age). The simplest assessment of the performance of a quantitative model with respect to a particular dataset is based on evaluation metrics such as the MSE. In many applications, it is preferable to provide a normalized metric such as the coefficient of determination ($R^2$), which is equivalent to the square of the correlation coefficient.

The second step is to establish the most appropriate model for describing the datasets collected. An international standard is provided by the WHO in the form of its growth chart for children’s development. As the WHO growth charts are based on data from other countries, it is important to understand how applicable the WHO model is for children from Rwanda. In order to provide an accurate assessment of the performance of different models and different datasets, we need to avoid over-fitting problems. Unfortunately, if the same data is used for estimating the parameters of the model and also for evaluating that model, it is possible that the procedure will over-fit the data and provide overly optimistic results as far as new dataset is concerned.

To remedy over-fitting we use cross validation, which is a model evaluation method that ensures that the evaluation is based on different dataset to that used to construct the model. Cross validation techniques tend to focus on randomly selected subsections of an entire dataset [7]. A k-fold cross validation approach was used to calculate a sum of the MSE for each fold, divide by the number of observations, and take the square root to obtain the cross-validated standard error of estimate. Data regarding the children’s weight was evaluated using an open source statistical package called ‘R’. ‘R’ has a k-fold cross validation function which calculates MSE for each fold, and the models presented in this chapter are evaluated using 3-fold cross-validation.

Another test used in the present study is the Kolmogorov–Smirnov (K-S) statistic that quantifies a distance between the empirical distribution functions of two samples [8]. For the two-sample case the null distribution of this statistic is calculated under the hypothesis that the
samples are drawn from the same distribution. The distributions considered under the null hypothesis are continuous distributions but are otherwise unrestricted, and K-S test is nonparametric.

5.3.2 Data Quality Dimensions
Defining data quality is the first step in the process of evaluation. Table 5.2 shows different dimensions of data quality that can be improved by electronic methods of collection. The dimensions are adopted from Baesens’ “Analytics in a Big Data World” [9], a classification commonly used in data analytics evaluations.

<table>
<thead>
<tr>
<th>Data quality dimension</th>
<th>Sub dimension</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intrinsic</td>
<td>Accuracy</td>
<td>Data correct</td>
</tr>
<tr>
<td></td>
<td>Reputation</td>
<td>Trusted source</td>
</tr>
<tr>
<td>Contextual</td>
<td>Completeness</td>
<td>Values present</td>
</tr>
<tr>
<td>Representational</td>
<td>Interoperability</td>
<td>Language and unit correct</td>
</tr>
<tr>
<td></td>
<td>Consistency</td>
<td>Ease of understanding</td>
</tr>
<tr>
<td>Accessibility</td>
<td>Accessibility</td>
<td>Easy to retrieve</td>
</tr>
<tr>
<td></td>
<td>Security</td>
<td>Access restricted</td>
</tr>
<tr>
<td>Additional digital data</td>
<td>Feedback</td>
<td>2 way communication</td>
</tr>
<tr>
<td>timeliness capability</td>
<td>Trends</td>
<td>Visual presentation</td>
</tr>
<tr>
<td></td>
<td>Timeliness</td>
<td>Instant availability</td>
</tr>
</tbody>
</table>

Table 5.2 Data quality dimensions adopted from ‘Analytics in a Big Data World’.

The case study provides the basis for considering the following of the above dimensions:

1) Accuracy: the present paper-based system does not have consistency checks while the electronic approach incorporates those features in the custom mobile application.

2) Consistency: by comparing the values that are input with a model based on previous measurements, it is possible to immediately detect errors and ensure self-consistency by prompting the data collector to revise the measurement.

3) Accessibility: electronic reporting is timelier than paper reporting since the present paper-based system is submitted only once a month. The web application designed for the case study displays the data as soon as the network synchronizes the mobile app with the web app.

4) Feedback: in a mobile collection system it is possible to get real-time feedback and have a two-way communication channel.
5.4 Data description and the model based on it
Along with electronically collected data on children’s weight in Rwanda we used paper records of the same CHWs to assess their quality. Both of those data sets are evaluated against an international standard provided by the WHO model. Table 5.3 provides detailed description of the three data sets.

<table>
<thead>
<tr>
<th>Data name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rwanda paper data</td>
<td>Paper data was obtained by recording children’s weight from the CHWs’ books in an excel spread sheet. Data contains information on weight and age for 320 boys and 380 girls. Those individual records are kept by the same CHWs participating in the case study.</td>
</tr>
<tr>
<td>Rwanda electronic data</td>
<td>24 participating CHWs collected data using a custom made smart phone mobile application. By the end of the study they collected information for 922 girls and 886 boys who live in their district. The data is collected over 9 months, and most of the data is cross-sectional, with about 330 children with time series data for 3-6 consecutive months.</td>
</tr>
<tr>
<td>WHO data</td>
<td>The WHO study was carried out in six different countries: Brazil, Ghana, India, Norway, Oman and the USA in year 2006. The WHO standards are based on a longitudinal study of 882 children aged 0–24 months and on cross-sectional studies of 6669 children aged 18–71 months. The WHO chart was used to simulate data for our study.</td>
</tr>
</tbody>
</table>

Table 5.3 Three different data sets, Rwanda paper, Rwanda electronic and WHO data set.

5.5 Results

Visualization of the plots obtained from the electronic and paper data collection gives an idea of the overall quality of the recording process, and of the nature of the growth and its variability with respect to the age of the child. Figure 5.3 shows the weight versus age of girls in Rwanda using electronic data (left) and paper data (right). Figure 5.4 does the same for Rwandan boys since boys follow a different growth pattern from girls, and all growth charts are separated by the sex of the child.
Table 5.4 compares four different evaluation studies, based on different datasets for training and testing. In each case, we use the log-log model for describing the relationship between weight and age.

We provide the parameter estimates and the cross-validated goodness of fit measure $R^2$. 

Figure 5.3 Electronic and paper data presenting weight and age for Rwanda girls.

Figure 5.4 Electronic and paper data presenting weight and age for Rwanda boys.
Based on a model structure of the form, log(weight) = a + b log(age), the training data was used to estimate the model parameters a and b. The four evaluation studies listed in Table 5.4 rely on three models as can be seen from the parameter values. In the following, these three models will be referred to as the Rwanda Paper model (evaluation A), the Rwanda Electronic model (evaluation B) and the WHO model (evaluations C and D). It was also possible to calculate the goodness of fit using the coefficient of determination, $R^2$, using a cross-validation approach. The $R^2$ values provided in Table 5.5 give quantitative support to the argument that electronic data collection is superior to paper-based data collection for both girls and boys in Rwanda.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
Evaluation & Training Data & Testing Data & Model & $R^2$ \\
\hline
A & Paper records & Paper records & log(weight) = 0.70 + 0.26*log(age) & 0.37 \\
\hline
B & Electronic records & Electronic records & log(weight)= 0.69 + 0.28*log(age) & 0.56 \\
\hline
C & Simulated data from WHO chart & Simulated data from WHO chart & log(weight) = 0.56 + 0.37*log(age) & 0.92^8 \\
\hline
D & Simulated data from WHO chart & Electronic records & log(weight) = 0.56 + 0.37*log(age) & 0.54 \\
\hline
\end{tabular}
\caption{Data sets, model parameter estimates and coefficient of determination ($R^2$) for Rwandan girls}
\end{table}

A direct comparison of traditional forecast evaluation criteria, such as MAE and MAPE provides a way to quantify the magnitude of the error in using a given model to make a prediction. Comparing a model of the form, log(weight) = a + b log(age) produces the following results for paper and electronic data sets, with the errors evaluated in units of kilograms. Electronic records provide considerable

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
Gender & Rwanda Electronic & Rwanda Paper & Gain in $R^2$ due to electronic approach \\
\hline
Girls & 0.56 & 0.37 & 51% \\
\hline
Boys & 0.58 & 0.35 & 66% \\
\hline
\end{tabular}
\caption{$R^2$ values for the model - log(weight) = a +b log(age), for boys and girl using Electronic and Paper collection, and gain in $R^2$ due to electronic approach.}
\end{table}

In the evaluation of the WHO chart, the goodness of fit ($R^2$) is very high because the same model is used to simulate both the training and testing data.
improvements over paper records, with at least a 40% reduction in error in both performance metrics, as shown in Table 5.6.

<table>
<thead>
<tr>
<th>Performance Metric</th>
<th>Rwanda Electronic</th>
<th>Rwanda Paper</th>
<th>Reduction in error electronic over paper data</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAE</td>
<td>1.4 kg</td>
<td>2.4 kg</td>
<td>40%</td>
</tr>
<tr>
<td>MAPE</td>
<td>12%</td>
<td>21%</td>
<td>42%</td>
</tr>
</tbody>
</table>

Table 5.6 MAE and MAPE of regression model evaluated using paper and electronic data sets for Rwandan girls, and reduction in error electronic over paper data.

In order to compare the data collected by the CHWs in Rwanda with the WHO growth chart, we plot the growth relationships arising from all three models on the same graph in Figure 5.5. As can be seen, there exists significant disparity. One possible explanation for the disparity between the WHO growth chart and the data collected in Rwanda (Figure 5.5) is that very young children in Rwanda usually benefit from breastfeeding up to their first birthday and therefore grow larger than the world average suggested by the WHO charts. When these babies start eating regular food, approximately around six months of age, they do not receive all the required nutrients and by the time they are year and a half old their weight falls below the WHO growth curve.
Another comparison is made between Rwanda electronic (evaluation B), using electronic data but coefficient estimates from the WHO regression (evaluation D). Table 5.7 shows two forecast performance metrics, MAE and MAPE, for the Rwanda electronic (evaluation B) and the WHO model (evaluation D), for Rwandan girls.

<table>
<thead>
<tr>
<th>Metric</th>
<th>WHO model (evaluation D)</th>
<th>Rwanda electronic (evaluation B)</th>
<th>Reduction in error of electronic model over WHO model</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAE</td>
<td>1.5 kg</td>
<td>1.4 kg</td>
<td>7%</td>
</tr>
<tr>
<td>MAPE</td>
<td>13.2 %</td>
<td>12%</td>
<td>10%</td>
</tr>
</tbody>
</table>

Table 5.7 Performance of evaluation Rwanda Electronic and WHO model for Rwandan girls using MAE and MAPE as metric, and reduction in error of electronic over WHO model.

From Table 5.7 it can be seen that the Rwanda Electronic model is outperforming the WHO model. The gain in performance of the Rwanda Electronic model is 10% for MAPE and 7% for MAE.
Finally we wish to test if this improvement in forecast performance is statistically significant. In order to do this, we applied a Kolmogorov-Smirnov test to the absolute percentage errors, which confirmed that the superior performance of the Rwanda Electronic model was statistically significant. Figure 5.6 presents Cumulative Density Functions (CDFs) of both Rwanda Electronic and WHO models (evaluation D), with the red line being Rwanda Electronic model and blue line WHO model. The K-S test finds the largest difference, vertically, and tests if that difference is significant, and in this case is statistically significant with p<0.01.

![Empirical CDFs](image)

**Figure 5.6 Comparison between empirical cumulative density function (CDF) for Electronic and WHO model.**

### 5.6 Conclusions
The pilot study provides ground for answering some of the questions posed about the data quality dimensions presented in Table 5.2.

1) **Accuracy**: Table 5.6 present performance metrics on the accuracy of models based on electronic and paper data. Electronic data improves upon the paper data by more than 40% in the case of both metrics (MAE and MAPE). Table 5.7 has same indicators for electronic data
against the WHO model for girls. The Rwandan Electronic model is 10% more accurate than the WHO model.

2) Consistency: real time consistency checks are available for electronic data whereas paper data has no checks until entered in the spread sheet or analyzed at later times.

3) Accessibility: electronic data can be accessed on the web application the same day it was recorded. Reports can be customized for a particular purpose.

4) Feedback: not implemented in the pilot study but participants expressed interest in real time feedback and a two-way communication.

General conclusions from the above analysis of data quality improvement can we summarized as follows:

- Electronic data records for Rwandan children have a goodness of fit, measured by $R^2$, which is more than twice that of the paper data records for both boys and girls.
- Electronic data and paper data collected from Rwandan children differ from WHO growth curves, raising doubts about the applicability of WHO growth charts to developing countries with considerable malnutrition.
- Comparisons of the electronic and paper data with the standard WHO model show that electronic data is closer to WHO model.
- Electronic data improves performance over the WHO model by 10% in mean absolute percentage error and 7% in mean absolute error. Results are statistically significant using the Kolmogorov-Smirnov test at $p <0.01$.

This study demonstrates that using modern telecommunications tools for health data collection that is automatically fed into EHRs, is allowing for improved tracking of health indicators. In this chapter we present evidence that electronic records are superior to paper records. We have also demonstrated that electronic records facilitate development of a country-specific model that is more accurate than the international standard provided by the WHO growth chart. The electronic collection of data and development of country-specific growth charts allows real-time monitoring.
5.7 Reference


6 Economic and Business Aspects of Mobile Health Intervention

6.1 Introduction

The previous chapters discuss technology adoption for monitoring health in low-resource settings, and present evidence that such a technological transition is feasible and improves data usability. However, the economic and business implications of such a transition require a different kind of feasibility that includes sustainability. Comparing cost and benefit provides evidence of the social value, while proposing a business model that would generate funding for such systems is necessary for the change to happen. An evaluation of social value should start with asking the following question: Would investing in reducing child malnutrition produce economic benefits that outweigh costs?

In this chapter we will consider only social cost and benefit. Undeniably, there are a range of private benefits related to monitoring children’s growth and development that result from early diagnostic and improvement in health outcomes. However, the cost of implementing digital data collection is unlikely to be borne by the Rwandan population so cost/benefit analysis would be limited to social cost and benefit. In addition, later in the chapter, a public-private partnership that enables cost sharing will be discussed.

This question has been addressed before in order to compare investments in nutrition with the competing claims for national resources to spur economic growth [1]. Such calculations face a number of obstacles, a major one including the time frame between the investments and the full range of economic gains, as well as the challenge of assigning a monetary value to each stream of benefits. In addition, the benefits will only be realized far into the future whereas the cost is more or less immediate. Consequently, the most important question becomes how to fund the cost and generate a stream of income much earlier than in the distant future. Designing a business model that would enable present day investments in projects with long term returns would offer long awaited solutions.
This chapter offers a model for cost-benefit analysis of an investment in monitoring the growth of children in order to detect and prevent consequences of malnutrition, in particular chronic malnutrition. Business options are discussed in general terms, and specific examples given that support them. The chapter starts with a brief description of the health consequences associated with malnutrition.

6.1.1 Consequences of malnutrition
A common measure of long-term nutritional deprivation that sets early in life is called stunting [2]. Stunting is defined as: “height-for-age below two standard deviations of the WHO Child Growth Standards median” [2], and often reflects the cumulative effects of under-nutrition or chronic malnutrition. Rwanda ranks the 18th highest position in the global malnutrition league table [2]. Early life consequences of stunting include higher susceptibility to infections and reduced cognitive ability. Long-term effects include the possibility of reduced earnings and an increased risk of contracting chronic diseases [3-5].

CHWs for this study collected weight-for-age variable for children in Rwanda because they had no equipment or training to collect height-for-age. However, Nguefack-Tsague et al. [6] show that if the height measurement is not available or accurate, then weight-for-age could be used instead. By using 3742 children aged 0 to 59 months, enrolled in a cross-sectional household survey (2004 Cameroon Demographic and Health Surveys (DHS)) covering the entire Cameroon national territory, the authors showed that weight-for-age could be used to accurately predict the nutritional status of children.

There is a growing recognition that in the Information Age, the potential of economic growth depends heavily on the quality of human resources more than ever before [7]. “Biological embedding”, a term used for the quality of the social and physical environment children grow up in, produces neural sculpturing that in some cases influences competence and coping in the children for the rest of their lives. That in turn produces a certain quality of the workforce which influences the development of a nation [6]. In addition, poor health and associated early mortality reduces a country’s measurement of
development known as Gross Domestic Product (GDP) by reducing both labor productivity and the relative size of the country’s labor force [8]. In practical terms, a suboptimal labor force as a consequence of inadequate nutrition has the power to hinder growth of a whole country or a region. Investing in monitoring children’s growth in order to detect and prevent their suboptimal development could be one of the investments with the highest return. Despite these proven consequences of child malnutrition in relation to the overall health of the child, very few studies calculate its impact on the development of a whole country. In the next sections, we develop methodology for calculating elements for cost-benefit analysis.

6.2 Cost/benefit methodology

6.2.1 Methodology for cost elements
The estimation of the cost in implementing EHR for monitoring children’s growth and development is based on the cost from this particular pilot project and it involves the following components: initial equipment, which was a smart phone for each CHWs, initial training of CHWs and software development, ongoing training, and the Internet connection for data transfers.

There are many options for data transmission and Table 6.1 presents three options. The first one is the most expensive and the version used for the pilot project and 24 CHWs, it is a full access to the Internet using data plan from a local mobile service operator. The second option is for the internal country network with limited access to the Internet but still enabling CHWs to unload the data on the local server, and such a network is planned for Rwanda in the near future. The third option is WiFi downloads when the CHWs visit the health center and this is the most affordable option. For the initial cost/benefit calculation the most expensive option will be considered with an idea that if the benefit-to-cost ratio is above one for the most expensive option it will be even better for the more affordable options.
When purchasing equipment for the case study (smart phones) we were not able to get a volume discount. However, it is reasonable to assume that the scale up cost per phone will be considerably lower. For the purchase of 4000 phones we assume the cost of $50 per item and for 40,000 phones $25 per item. In Table 6.1, the green numbers are associated with alternative 1 (internal network), and the blue numbers with alternative 2 (WiFi uploads).

<table>
<thead>
<tr>
<th>Type of cost</th>
<th>24 CHWs ($)</th>
<th>4000 CHWs $50/phone</th>
<th>40,000 CHWs $25/phone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment</td>
<td>2,400</td>
<td>200,000</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Initial training and software development</td>
<td>384</td>
<td>64,000</td>
<td>640,000</td>
</tr>
<tr>
<td>Ongoing training</td>
<td>120</td>
<td>20,000</td>
<td>200,000</td>
</tr>
<tr>
<td>Full Internet connection</td>
<td>360</td>
<td>60,000</td>
<td>600,000</td>
</tr>
<tr>
<td>Alternative 1: internal network within the country</td>
<td>240</td>
<td>40,000</td>
<td>400,000</td>
</tr>
<tr>
<td>Alternative 2: WiFi at the health center</td>
<td>48</td>
<td>8,000</td>
<td>80,000</td>
</tr>
<tr>
<td><strong>Total cost</strong></td>
<td><strong>3,264</strong></td>
<td><strong>3144</strong></td>
<td><strong>2,440,000</strong></td>
</tr>
</tbody>
</table>

Table 6.1 Cost of scaling up for the investment in mobile technology for health data collection.

In equation (3-8) from section 3.5.4 the present value of the general total cost function is detailed:

\[
C_0 = E_0 + T_0 + \sum_{t=1}^{N} d^t (D_t + T_t)
\]  

(6-1)

where:

- \(C_0\) – present value of the total cost
- \(E_0\) – initial equipment cost, at time zero initial equipment is assumed to have lifetime of 5 years or duration of tracking one cohort of children form age zero until the age of five
- \(T_0\) – training cost at time zero
- \(T_t\) – cost for training at time t, evaluated at year’s end
- \(D_t\) – cost of data transmission at time t, evaluated at year’s end
- \(t\) – number of years from when the cost occurs,
- \(N\) – the length of the trial is 5 years
- \(d\) – discount factor, \(d = \frac{1}{1+i}\) where i is the discount rate

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For purpose of the cost evaluation we will consider five years of monitoring, one group of children from birth until the age of five, so $t = 5$. For the specific calculation regarding Rwanda a discount rate of 12% is used [13], which implies the discount factor $d = 0.89$.

From Table 6.1 the initial cost for CHWs is $1,640,000 at time $t=0$. Using the discount factor of 0.89, to find the present value of all the reoccurring cost during the five year period and adding to the initial cost produces the following present values of total cost:

$$C_0 = 1,640,000 + 800,000 \times \sum_{t=1}^{5} \left( \frac{1}{1.12} \right)^t = 4,520,000 \quad (6-2)$$

The next section describes the benefits from averting malnutrition and calculates a present value of such benefits for Rwanda.

### 6.2.2 Methodology for benefits

Benefits are much more difficult to calculate because they are less obvious and precise. In the literature, most studies [14-15] separate benefits into: short term health benefits that produce savings in health care cost; and longer term benefits that improve earning power for properly nourished children. Table 6.2 shows both short and long term benefits and their time span.

<table>
<thead>
<tr>
<th>Benefit elements</th>
<th>Years after monitoring/benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shorter term benefit (STB)</strong></td>
<td>1-15 years (school age)</td>
</tr>
<tr>
<td>Cognitive development</td>
<td>Physical and intellectual growth</td>
</tr>
<tr>
<td>School participation</td>
<td>More years of schooling</td>
</tr>
<tr>
<td>Reduced cost of medical care</td>
<td>Improvement in overall health</td>
</tr>
<tr>
<td>Reduced inequality</td>
<td>Smaller social differences</td>
</tr>
<tr>
<td><strong>Longer term benefit (LTB)</strong></td>
<td>15-60 years (productive age)</td>
</tr>
<tr>
<td>Demographic changes</td>
<td>Improvement of social status</td>
</tr>
<tr>
<td>Higher earning power</td>
<td>Higher salary and wealth</td>
</tr>
<tr>
<td>Healthier labor force</td>
<td>Reduction in chronic diseases</td>
</tr>
</tbody>
</table>

Table 6.2 Short and long term benefits resulting from the proper nutrition of children under five
Based on Table 6.3 and the equation (3-9) described in section 3.5.4 the present value of discounted benefit per child could be calculated using the following:

\[ B_0 = \sum_{t=1}^{N_s} d^t S_t + \sum_{t=N_s+1}^{N_l} (d^t g^t) L_t \]  

(6-3)

where:

- \( B_0 \) – present value of the total benefit
- \( S_t \) – shorter-term benefit per child from mHealth solution at time \( t \), evaluated at year’s end
- \( L_t \) – longer-term benefit per child from mHealth solution at time \( t \), evaluated at year’s end
- \( N_s \) – number of years of the shorter term benefit per child at time \( t \), evaluated at year’s end
- \( N_l \) – number of years of the longer term benefit per child at time \( t \), evaluated at year’s end
- \( t \) – number of years from when the benefit occurs
- \( g \) – rate of economic growth

For short term benefits, the time ranges from 1 to 15 years, from the age of 5 to 20 or until the child grows up to be a productive member of society. Those benefits result from reduced cost of medical care, better school participation, better cognitive development, and reduced inequality. After the child reaches adulthood, the main long term benefit that will be considered is increased earnings, and a specific calculation adopted from a previous study \([4]\) that found reducing malnutrition increases earning by 14%. That particular study by Alderman et al. \([4]\) followed 665 children in Zimbabwe over a long period of time and isolated the effect of malnutrition on earning power. Rwanda and Zimbabwe are similar in political history and poverty levels but Zimbabwe has a lower level of malnutrition (28%) than Rwanda (44%) \([14]\).

The time interval for long term benefit is 16 to 60 years from the intervention or the child’s productive life time, between the ages of 21 to 65. In order to calculate specific numbers for reduction in earnings for Rwanda, we take an average salary in Rwanda which today is $270 \([16]\). The gain in earnings from Alderman et al. \([4]\) is 14% of the average salary, and that would be $37.8, applying real growth rate of the Rwandan economy, which is 8% \([16]\), implying that salaries and the differential in
earnings will grow at that rate. Combing that growth rate with the same discount factor \( d = 0.89 \) as for the cost function [13] the effective discount rate will be 3.6%.

To obtain the total effect we use the UN report [17] which says that in 2012 Rwanda had approximately 2 million children under five and 44% of them are stunted as a result of chronic malnutrition [18]. This means that about 880,000 children in Rwanda could benefit from better monitoring of growth and development to improve nutrition. Based on Svedberg, [18] we assume that about 10% of those malnourished children would improve their nutritional status which for Rwanda means 88,000 children.

The present value of accumulated long term earnings per child, during a child’s productive life, from the age of 21 until 65, in specific terms for Rwanda is:

\[
B_0 = \sum_{t=21}^{65} \frac{37.8}{1.12^t} = \$37.8 \times 10.5 = \$396.9
\] (6-4)

If we estimate the total long term benefit using figures that Rwanda now has 2,000,000 children below the age of five, of which 44% are malnourished, and adopt from the previous work [18] that 10% of those malnourished children would improve their health status because of monitoring, we get a total of 88,000 children that will gain from monitoring. Consequently, the total amount of discounted benefits from a long term savings for present day Rwanda is:

\[
B_0 = $396.9 \times 88,000 = $34,927,200
\] (6-5)

or approximately $35 million.

In comparison, there have not been any studies estimating short term benefits such as reduced cost of medical care and reduction in equality that could be applicable to Rwanda. Consequently, for the purpose of a specific calculation for Rwanda we will concentrate only on the long term benefits. Short
term benefits are substantial but there is no adequate study that allows quantitative estimates for Rwanda.

The next section explores the effect of the numerical assumptions by executing a sensitivity analysis.

6.3 Ratios and Sensitivity Analysis

6.3.1 Calculating benefit-to-cost ratio for electronic data collection

The previously described assumptions produce the benefit-to-cost ratio:

\[ R_0 = \frac{B_0}{C_0} = \frac{34,927,200}{4,520,000} = 7.73 \]  

(6-6)

Such a high number should not be surprising because the benefit from reducing even a small percentage of malnourished children could have a substantial effect on countries with a large proportion of young people. Most African countries have predominately young populations with a significant number of children being malnourished. For them, a key concern would be how to finance the cost in a country with a low GDP. One way to approach the funding issue is to develop a business model that would generate revenue from the conception of the project.

One assumption that could be varied is that 10% of children would benefit from monitoring. Reducing that to an extremely low level of 1% would imply improvement for only 8,800 children. In that case, the benefit would reduce to $3,492,720. That would produce a benefit-to-cost ratio of 0.77, which is below 1.0. For the benefit-to-cost ratio to be above 1.0, the percentage of children who improve because of the intervention has to be above 1.3%, which is a rather small improvement and easily attainable.

Placing the above benefit-to-cost ratio (7.73) in perspective, it is interesting to compare it with the findings from a recent study [19], where authors construct estimates of benefit-to-cost ratios for a
variety of nutritional interventions to reduce stunting. The study by Hoddinott et al. [19] calculates those ratios for eight different countries in Africa plus nine other low income countries which they call high-burden countries. Their assumptions are different in two ways. They use a discount rate of 5% which implies discount factor of 0.95, and a lower estimate for salary differential of 11.3%. Otherwise the benefits are also underestimated by taking into account only longer term benefits and only public benefits. Their estimates of benefit-to-cost ratio range from 3.8 to 47.9, with 18.4 as a median.

Unfortunately Rwanda is not on the list of African countries but there are several East African countries and Rwandan neighbors such as DRC with the benefit-to-cost ratio of 3.8, Kenya with the ratio of 18.7 and the closest country to Rwanda - Uganda with the ratio of 14.1. The estimate from the present study with the ratio of 7.73 is the closest to DRC.

<table>
<thead>
<tr>
<th>Income growth due to reduction in stunting</th>
<th>Discount factor for benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>14% (present study)</td>
<td>0.96 (present study)</td>
</tr>
<tr>
<td>11.3% (Hoddinott)</td>
<td>0.95 (Hoddinott)</td>
</tr>
<tr>
<td></td>
<td>7.73</td>
</tr>
<tr>
<td></td>
<td>6.23</td>
</tr>
<tr>
<td></td>
<td>4.93</td>
</tr>
<tr>
<td></td>
<td>3.98</td>
</tr>
</tbody>
</table>

Table 6.3 Sensitivity of benefit–cost ratio estimates to assumption of impact of stunting reduction on income growth and on the discount rate used

Table 6.3 presents results of the sensitivity investigation to variations of the discount factor and the income growth in benefit-to-cost ratios when changing the discount factor and income growth to match the Hoddinott study [19]. The income growth is reduced to 11.3% and discount factor for benefits is matched the Hoddinott study [19]. The ratio is significantly lower showing sensitivity to reduction in both of the rates, with discount rate having more impact than the salary differential. Applying both rates the benefit-to-cost ratio reduces to 3.98, very close to the DRC ratio of 3.8 from the Hoddinott study [19].
The main difference of the present study is the implication that tracking growth and eating habits of children under five could make significant difference in children’s growth and development, while all other studies investigate the impact of nutritional intervention by outside entities.

**6.3.2 Benefit-to-cost ratio for paper data collection**

In general, cost/benefit analysis is used for comparing alternatives, and as such warrants comparison of the benefit-to-cost ratio of electronic monitoring to the existing system, paper monitoring. Since the estimates for improvement in child’s development [18] are not specifically tied to the electronic monitoring but any type of consistent monitoring the same type of benefits could be applied for the paper monitoring. However, the present system of paper monitoring is not tracking individual children on a centralized level, instead CHWs keep them in their notebooks and report only aggregated figures. Assuming that could be modified to a consistent individual child monitoring by CHWs, the equipment costs, such as paper notebooks, are considerably lower than the cost for electronic monitoring. However, there are several additional costs to expending the present paper system: 1) it would require training CHWs in monitoring techniques, such as calculating trends in child’s growth; 2) also having no remote feedback, CHWs would have to be trained to estimate when the actual growth is significantly outside the anticipated or predicted trend. Most importantly the electronic system is superior in data quality to the paper system so there should be a cost associated to the reduction in data quality.

Other issues would be reaching remote locations in a timely manner. From 2005 to 2012 stunting in Rwanda reduced from 51% to 44% overall [20] but the rate was very uneven regarding urban versus rural location. In 2012 in urban locations there were 27% stunted children and 47% in rural, with Northern and Western provinces being the worst [21]. One considerable advantage of electronic data collection is that the feedback could reach rural locations in a timely manner.
Considering that acquired health data could have other potential value, it would be possible to use that information as a basis for a data driven business. In effect, the more useful data CHWs collect the more valuable their service becomes. After training CHWs and providing them with smart tools for electronic data collection CHWs could collect valuable health information for prevention and early detection of many diseases. In addition to the health data, CHWs could collect environmental data, agricultural data and even commercial data. Such data driven business could generate funds soon after implementation, and provide the return on the investment that justifies the project.

The next section discusses a possible business model that would generate funding at the present time and allow investment in projects with long term and distant future benefits.

### 6.4 Business model

#### 6.4.1 Introduction

A business model is a sustainable way of doing business, where the sustainability is defined as a concept that allows an entity to survive over time and create a successful, even profitable, business in the long run [20]. The reason for this apparent ambiguity around the concept of profitability is that business models apply to many different settings other than the profit-oriented company. The application of business models is much broader and is a meaningful concept both in relation to public-sector administration, NGO’s, schools and universities, and even individuals.

A relatively new approach [22], called business canvas, recommends a template for developing new or documenting existing business models, and is a visual chart with elements describing a value proposition, infrastructure, customers, and finances. It assists companies in aligning their activities by illustrating potential trade-offs. The next section details those basic concepts in general and then in the later part it is applied to a health data collection business.
6.4.2 Business Canvas background

Business Canvas follows the main stream concept of creating value while delivering a product or service to customers, and it elements are the following:

- Value proposition (problem or need to solve)
- Customer segments (who is served)
- Channels (physical and/or web/mobile)
- Customer relations (get/keep/grow)
- Revenue stream (where the money comes from)
- Key resources (assets)
- Partners/Suppliers
- Key activities
- Cost and expenses

What is novel about Business Canvas is the way it treats customer discovery. It demands the entrepreneurs to go out of the building and interview people, ask them about a product or service, and try not get tied to a specific customer, features or revenue stream. It suggests testing the hypothesis and then pivot if customer needs do not match the initial idea.

Business canvas has four stages of customer development:

1. Customer discovery
2. Customer validation
3. Customer creation
4. Company building

The main differences between a business plan and business canvas are:

**Business plan**
- one way street in presenting information and ideas
- entrepreneur has an idea and then writes a document about it
- includes a prediction of balance sheets and future finances

**Business canvas**
- has several iterative versions
- entrepreneur goes out and tests the idea on potential customers
- it pivots (changes) if not correct
finds the metric that really matters

The challenge would be to find a business model using Business Canvas for the newly acquired skills of community health workers, along with a new usability of the data they collect. On major benefit from the project was a capacity building as an outcome of the trainings on how to use technology and how to collect data. Those new skills could be the basis for the business model that would allow CHWs entrepreneurial opportunities. The next section presents a version of business canvas for the health data collection project.

### 6.4.3 Business Canvas for health data collection

Identifying usability of the health data could provide us with potential customers and a value proposition. Data indicating spread of communicable diseases, food consumption, trade, and population growth could be useful to insurance companies, local and global commercial businesses, government entities and NGOs.

Sweet [23] identifies four strategic value configuration logics for the service economy: value-adding, -extracting, -capturing, and -creating, that exist no matter the prevailing economic paradigm. For the health data, usability of value-adding is a powerful product but it would require trained data analysts. The same applies for value-extracting and -creating. However, value-capturing would only require CHWs to collect health data about underserved population and such data could be valuable to many customers who would otherwise need to go and collect such data using their own resources.

Figure 6.1 provides a visual representation of the business canvas with important elements for a business based on health data collection. The center point in the canvas is a value proposition. In this case, the value proposition is stated as the following: “CHWs provide real-time data from their community at affordable prices”. CHWs live in underserved communities implying that there is very little data available about those communities, in particular real-time data. With modern telecommunication
tools and widely accessible cellular network in countries such as Rwanda, real-time data becomes a reality.

![Figure 6.1 Business canvas for health data collection model for CHWs](image)

Other important aspects of business canvas are revenue streams and key partners. In Figure 6.1, the revenue stream comes from insurance companies, NGOs and many branches of government that can use these newly available data. International businesses could be potential buyers of data, while local businesses would need to learn about its usefulness first and at the present time are the least likely to purchase data. Partners in the proposed canvas are telecommunications companies who at the present time already collaborate with the Ministry of Health in Rwanda and who would benefit from expanding 3G services. Another partner in data acquisition could be international or regional community, especially when the spread of disease is concerned.
The next section presents a case study that follows a business model based on digital technology and dissemination of information in rural communities. This case study provides an alternative that in combination with the above proposed business model could provide sustainable funding for health interventions.

6.4.4 Case study from Bangladesh

“Info Lades” is an entrepreneurial experiment conducted in Bangladesh and is best described by a quote from Ahmed et al. [24]. “... Info Ladies are women who receive specialized training and technology, and then travel to remote areas to personally connect villagers to the information and resources they need. The ‘Info Lady’ model, a natural extension of mobile lady, an innovative initiative developed by D.Net, (Development Research Network) Bangladesh, a nonprofit research organization that champions the use of ICT for the economic development of Bangladesh, has overcome problems such as computer illiteracy and high implementation costs that are associated with providing computers directly to villagers. In a bag on bicycles, the ‘Info Lady’ carrying an Intel-powered classmate PC, a mobile phone with Internet connectivity, a digital camera and a headphone set, covers 15 villages to provide information services in terms of health, agriculture and communication at a lower cost.” The organization behind this project is D.Net [25] which recruits the women and trains them for three months to use a computer, the Internet, a printer and a camera. In addition, it arranges bank loans for the women to buy bicycles and the necessary equipment.

Figure 6.2 shows those ladies traveling to rural areas in their uniforms using bicycles. The services they provide are related to livelihood information and knowledge, health, government services, and international and local voice calls. They help villagers with online banking, filling passport forms online, applying for any government-related services such as pensions and special funds for the freedom fighters or filling application forms for university. From a health perspective, they discuss sexual harassment, dowry, under-age marriage, hygiene and HIV.
This is a “push” system because it disseminates information and in effect replaces mobile kiosks with value added services such as support in the form of advice for certain issues. Villagers pay for the service, for example 200 takas ($2.40) for an hour of Skype time [26]. Recently Bangladesh's central bank became a partner in the project which agreed to offer interest-free loans to Info Ladies. Distribution of the first phase of loans, totaling 100 million takas ($1.23 million), will begin in December 2015 [26]. At this point there are nearly 60 Info Ladies working in 19 of Bangladesh's 64 districts. By 2016, the CEO of D.Net hopes to have trained 15,000 women.

What makes this case study interesting is the possibility of combining both business models: push and pull of information. The next section details an idea of how that combination could work.

### 6.4.5 Combining push and pull models

One possible business model would be combining a Rwandan and Bangladesh approach and establishing an independent agency providing “Info CHWs” which sell access to information in the rural areas of a developing country. At the same time, they would collect information, including health or other types of
data, which could add value to other entities in the system. Combining push and pull of information could provide a sustainable model that could support itself and at the same time produce enormous social benefits, as calculated in section 6.2.3 Methodology for benefits.

Testing this approach would require a field study that includes four steps of customer validation and belongs to future work based on this thesis.

6.5 Conclusions
This chapter discusses the economic and business aspects of implementing a health intervention based on mobile technology. It first presents cost elements associated with using electronic and telecommunication devices for health data collection. Then the benefits are outlined and one particular long-term benefit calculated for the Rwandan economy and society. Comparing cost and benefits by calculating benefit-to-cost ratio for a present day Rwanda establishes a high ratio of 7.73. However, the timing of cost and benefits differ and a business model is developed that offers a solution on how to fund costs at the present time without waiting for the future benefits.

Testing the above proposed business canvas largely belongs to the future work because it would require a field study following a customer discovery process from the business canvas model. Finally, a combination of the proposed business model with a different business approach from Bangladesh is discussed and proposed.
6.6 References


7 Conclusions
Work presented in this thesis has a multidisciplinary approach in regards to the analysis of the implementation of smart phones in health data collection in limited-resource settings. It starts by testing TAM in limited recourse settings, and then it evaluates the feasibility and usability of a specific mobile health application. It also demonstrates that the use of modern telecommunications tools for health data collection that is automatically fed into EHRs, has improved tracking of health indicators. It ends by discussing the economic and business aspects of implementing a health intervention based on mobile technology, and proposing a business model that could ensure sustainability.

7.1 Summary of Results
7.1.1 TAM and usability of the application
The evaluation of TAM in a limited resource setting started with inquiring about the attitudes of physicians and then CHWs towards mobile technology in the health space. Both surveys suggest that physicians and CHWs are willing to adopt technology if they find it useful in their practice. Both groups find usefulness and ease of use important, and the weights of these two components are skewed towards usefulness for the physicians and are equal for the CHWs. Physicians are willing and eager to improve efficiency in receiving results from investigative labs, outpatient consultations, research and for managing meetings. It was easier for CHWs to adopt new technology for a task that was familiar to them, than to learn a new task while changing the implementation tool. The difficulty arose when using a new tool and learning a new methodology at the same time. However, they found mobile technology appealing in providing real-time feedback and access to previously collected data.

The survey of Rwandan NGOs and companies concluded that the general awareness and adoption of IT for data collection is low. Within the survey participants, a small number of foreign NGOs and some private companies are already using tablets and mobile phones to collect data for their own use and for organizations that base their decisions on primary data. However, most NGOs and private
organizations remain reluctant to change because of the low ICT awareness of the Rwandan population, despite understanding the value of timely and relevant data.

During the pilot project, CHWs reacted positively towards a custom mobile application and found its usability sufficiently high to maintain use for nine months. The added benefit of having access to the Internet kept them interested in the system, and it took several weeks for the urban group and several months for the rural group to become familiar with the new system.

The usability of the custom mobile application in the project from the aspect of effectiveness was high, and the health records of approximately 2000 children were recorded in the system. The level of efficiency was measured by the time needed to train users with no prior experience, and that was two training sessions, each 4 hours long. Satisfaction with the new system of all 24 users was extremely high.

The lessons learned, presented in section 4.4.5, and the scaling up estimates, in Table 4.6, based on this pilot project inform policy makers in Rwanda and the East African region, where most countries base their health system on community health workers. In addition, CHWs are the backbone of many Asian countries, such as India, Pakistan and Bangladesh, and this pilot project and the proposed mobile data collection could be useful for them as well.

In summary, Rwandan doctors and CHWs who were participants of this study understand the benefits mobile technology can provide to their practice and both the perceived usefulness and ease of use as important factors. Both groups were eager to adopt mobile technology, which they perceived as a way to reduce burdens they experience in a resource-limited setting. During the field study, CHWs were very satisfied with the mobile application and were effective in data collection, while the scaling up estimates are encouraging for developing countries with health systems similar to Rwandan.
7.1.2 Data quality

Data quality evaluation was a significant part of this work and the results show that electronic data collection is superior in quality to paper data collection. In addition, electronic data enables the design of a country specific growth chart that performs better in predicting the growth of Rwandan children under five than the standard WHO growth chart. The data quality is evaluated using two metrics: Mean-Squared-Error (MSE); and Mean Absolute Percentage Error (MAPE). The following four different dimensions of data quality are adopted from the literature [1] on data analytics:

5) Accuracy: electronic data improves upon the paper data by more than 40% in the case of both metrics (MAE and MAPE). The Electronic Rwandan growth model is 10% more accurate than the WHO growth model.

6) Consistency: real time consistency checks are available for electronic data whereas paper data has no checks until entered in the spread sheet or analyzed at later times.

7) Accessibility: electronic data can be accessed on the web application the same day it was recorded. Reports can be customized for a particular purpose.

8) Feedback: not implemented in the pilot study but participants expressed interest in real time feedback and a two-way communication.

In addition, as presented in section 5.5, the study provides grounds for the following conclusions:

- Electronic data records for Rwandan children have a goodness of fit, measured by $R^2$, which is more than twice that of the paper data records for both boys and girls.
- Electronic data and paper data collected from Rwandan children differ from WHO growth curves, raising doubts about the applicability of the WHO growth charts to developing countries with considerable malnutrition.
- Electronic data improves performance over the WHO model by 10% in MAPE and 7% in MAE. Results are statistically significant using the Kolmogorov-Smirnov test at $p < 0.01$.

In summary, this study demonstrates that using modern telecommunications tools for health data collection that is automatically fed into EHRs, is allowing for improved tracking of health indicators. It
presents the evidence that electronic records are superior to paper records, and demonstrates that electronic records facilitate development of a country-specific model that is more accurate than the international standard provided by the WHO growth chart. Finally, the electronic collection of data and development of country-specific growth charts allows real-time monitoring.

7.1.3 Econ/business aspect
Cost/benefit analysis produced results with an overwhelmingly higher present value of benefits than the present value of costs, producing a high benefit-to-cost ratio.

The estimation of the cost in implementing EHR for monitoring children’s growth and development is based on the cost from this particular pilot project and it includes the following components, presented in Table 4.6: initial equipment, which was a smart phone for each CHWs, initial training of CHWs and software development, ongoing training, and the Internet connection for data transfers. After scaling up to 40,000 CHWs, and using the Rwandan discount rate of 12% [2], the present value of the total cost is calculated to be about $4.5 million.

Benefits are separated into shorter term health benefits that produce savings in health care cost; and longer term benefits that improve earning power for properly nourished children. However, there have not been any studies estimating short term benefits, such as reduced cost of medical care and reduction in equality, which could be applicable to Rwanda. Consequently, for the purpose of a specific calculation for Rwanda, we considered only the long term benefits, which is an improvement in earning power. Those longer term benefits are estimated for present day Rwanda that has 2,000,000 children below the age of five, of which 44% are malnourished [3], and adopted from the previous work [4] that 10% of those malnourished children would improve their health status because of monitoring. We obtained a total of 88,000 children that will gain from growth monitoring, and using the same discount factor as for the cost [2], obtained the present value of benefits to be approximately $35 million.
Finally, as presented in section 6.3, comparing cost and benefits of the suggested mobile application by calculating a benefit-to-cost ratio, for a present day Rwanda, results in a ratio of 7.73, which has over seven times higher benefits than cost. That is a significantly high ratio, however, a concern is that the timing of the cost and benefits differ, and a business model is developed that offers a solution on how to fund costs at the present time without waiting for the future benefits. The field evaluation of the business model is greatly in the scope of future work that is outlined in the next section.

### 7.2 Future Work

The real value of this type of research is its scalability to other countries and regions. The present study opens many questions about technology adoption in developing countries, as well as data availability and quality. Sustainability is another major unresolved question in ICTD research.

The pilot project was conducted in two locations and with a small number of CHWs. Scaling up to the whole of Rwanda is a non-linear transition with economies of scale when it comes to purchasing equipment, but with organizational obstacles and implementation in remote rural areas posing serious challenges. Almost all other countries in East Africa base their health systems on CHWs and have a developed mobile network that would allow mobile data collection. Scaling up this project to other countries with similar health systems would require localization in language, adjustment of the nutritional survey to allow for cultural aspects of food assortments, and adjusting to the specifics of the country CHWs functions. Applying the same concepts to Asia where CHWs have a major role in health monitoring would require further adjustments. However, this study undeniably shows that data quality improves with the use of electronic tools and that users with no previous experience could be trained in a short time frame to perform sophisticated data collection using smart phones and third party applications.
The sustainability of such interventions would have to be addressed on a country-by-country basis considering internal rules regarding data sharing and privacy. In the present study, the rules of the Rwandan Ethics Board were applied to data anonymity and aggregation. Allowing businesses based on collecting health data to use the data might not be acceptable in some countries and alternative approaches could be explored.

The next section describes academic collaborations based on this study and plans for the future publications.

### 7.2.1 Ongoing collaborations

One idea for the extension of this work is to look beyond usefulness and ease of use into aspects of Human Computer Interaction (HCI), in particular mobile devices and HCI. In a paper on the “The Future of Mobile Devices in HCI”, J. Wobbrock [5] stresses the potential benefit of mobile phones in Africa is the delivery of medical and health information, particularly to rural areas. Professor Anders Henton from Aalborg University, Aalborg, Denmark, proposed looking into appropriation as the process by which people adopt and adapt technologies, fitting them into their working practices. He and I are going to work together on a paper exploring reasons for improvement, building on the HCI tradition: Why are Electronic records so much better than the Paper records?

Testing the proposed business canvas in section 6.4 also belongs to the future work because it would require a field study following the customer discovery process from the business canvas model. In addition, Professor Faheem Hussain, from the Department of Technology and Society at SUNY Korea, is working with me on a paper addressing health entrepreneurship, and drawing parallels between Rwanda and Bangladesh from the aspect of business applications.

A relatively new field in ICTD, Data for Development (D4D), has emerged by using already available data from mobile phones. Developing countries lack data on many social and human
attributes, as well as transactions. An attempt to approximate missing information has been completed using Call Detail Records (CDRs). CDR contains metadata of each instance of a specific telecommunications transaction. It typically contains the following attributes: the originating phone number, the receiving phone number, timestamp, the towers to which those phones are connected, call type (voice, SMS). That data is often combined with the health data in order to make inferences about a health issue. Based on my work presented in Chapter 5 with a visiting professor at CMU Rwanda, Patrick McSharry, an author of “Big Data Revolution” [6], we are working on a model to approximate health of the population in Kigali using CDRs and health data.
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