First-Mile Accessibility to Health Services: a mHealth Model for Rural Uganda

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Abstract

This study estimates the disconnection in rural Low-Middle-Income Countries (LMIC) between the First-Mile suppliers of healthcare services and the Last-Mile end-users. This detachment is due to geographical barriers and shortage of technical, financial, and human resources. Prompt diagnosis and treatment are vital for rural communities. Public and private savings can be generated by introducing mHealth technologies, considering the remote users as the prospective market for mHealth application to diseases like malaria. Users typically have easier access to cell-phones than hospitals, so mHealth can help overcoming such barriers, transforming inpatients/outpatients into home-patients, decongesting hospitals, especially during epidemics. This generates savings for patients and the healthcare system. The advantages of mHealth are well known, but there is a literature gap in the description of its economic returns. This study applies a geographical model to a typical LMIC, Uganda, quantifying the time-cost to reach an equipped medical center. Time-cost measures the disconnection between First-Mile hubs and Last-Mile hotspot, the potential demand of mHealth by remote users, and the consequent savings. The study measures an average time-cost of 75 minutes, well above the recommended thresholds, and estimates that mHealth leads to significant savings (1.5 monthly salaries and 21% of public health budget). Community health workers and private actors may re-engineer healthcare resources through Public-Private Partnerships (PPP), remunerated with results-based financing (RBF). These findings can contribute to improving healthcare resource allocation in LMIC.

Keywords: Barriers to care; remote diagnosis; Geographic Information Systems; home-patient; Results-based financing; healthcare cost-effectiveness.

1 Background

This paper aims to study the mismatch between healthcare supply and needs in Uganda, identifying the demand for m-health and estimating the savings in healthcare deliveries enhanced by mHealth services.

The framework is represented by a Healthcare Supply Chain (HSC) in which health products (namely goods, services, and information) flow from the earliest supplier to end-users. It includes people, processes, policies, technology, and resources aimed to ensure that the right health product reaches the right place in the right conditions and time [1].

An efficient HSC can ensure healthy lives and contrast preventable diseases and safeguard the financial investments by governments and donors. A crucial step of the HSC is the complex connection between the First-Mile healthcare centers and the Last-Mile hotspots. The former are the facilities run by medical doctors that perform primary diagnosis, essential lab tests, and emergency surgery; the latter are all those that benefit from First-Mile healthcare products. Lack of skilled and trained personnel, equipment, and funding hinders an efficient implementation and

management of First-Mile and Last-Mile connections, especially in Low and Middle-Income Countries (LMICs) [2].
These limitations are particularly evident in backward rural areas, where First-Mile hubs are typically understaffed, being operated by only one or two health professionals, often not medical doctors, with limited training, and offer a limited range of services. Moreover, they are accessible via small (unpaved) roads or tracks, and some are off the electrical grid [3].
Worldwide, more than one billion people lack access to healthcare only due to geographical distance [4]. Information exchange between First-Mile and Last-Mile is also very poor and inaccurate, leading to a lack of coordination, management, and audit, with consequent poor governance and accountability of HSC [5-6]. This misconnection leads to very poor delivery of primary health products and services in many parts of the world, and thus to high mortality rates, especially for children [7].
Currently, in many LMICs, the connection between First- and Last-Mile is managed by Community Health Workers (CHW) who attempt to bring lifesaving care to the doorsteps of those living at very remote last mile [8]. CHW are a para-professional health workers, who are members of the communities where they work, and thus have an in-depth understanding of the community culture and language. They have received standardized job-related training of a shorter duration than health professionals, and their primary goal is to provide culturally appropriate health services to the community [9]. However, CHW programs are limited by lack of adequate supervision, continuous education, and proper information and logistic support [10-11].
In sub-Saharan Africa, several hundred million people, who never used traditional landlines, now use mobile phones regularly [12]. This has ignited the African communications revolution, generating optimism that mobile phones might benefit rural communities by developing new opportunities and innovation. The use of Short Messaging Service (SMS), wireless data transmission, voice calling, and smartphones to transmit health-related information has been offering the opportunity to overcome the First- and Last-Mile disconnection, improving access to healthcare services [13-14]. These various technologies, collectively named "mobile health" or "mHealth" [15], have touched the boundaries of hard-to-reach areas, positively affecting healthcare in African LMICs [16].
mHealth softens some HSC bottlenecks as infrastructural deficiencies, limited access to medical care, and the shortage of skilled healthcare workers [12, 17-19]. African LMICs have been embracing mHealth to improve primary healthcare delivery, and consequently, the scientific literature on mHealth is growing. SMS are the most advanced mHealth technology, used to communicate to local communities the updates on the availability of clinical services [20] or to overcome poor home management of treatments by patients with chronic disease [21]. Furthermore, mHealth is used to support the performance of CHW, disseminating clinical updates, learning materials, and reminders. This is the case mainly where CHW deliver integrated community case management to children sick with diarrhoea, pneumonia, and malaria [22-23]. Moreover, mHealth is also used to evaluate and monitor the performance of the healthcare system [24]. Although these mHealth applications reported positive results, especially in disease control, prevention, and surveillance [25], formal mHealth programs remain limited in coverage and scope [17]. This happens especially in resource-poor settings, and the lessons learned about their use in such environments are yet to be collected [26]. Empirical evidence about the effectiveness of mHealth on healthcare outcomes is insufficient [27], and mHealth is still at an early stage of development in LMIC [28-29].

2 Literature gaps

In the wide scientific literature on mHealth, there are still gaps, represented, for instance, by the shortage of analysis and evidence on the savings and financial impacts generated by mHealth applications [13-16]. An economic impact analysis is, however, rarely carried out in support of theses advocating mHealth adoption.

A systematic review of economic evaluations of mHealth solutions highlights how only a few studies examine in depth this aspect. Most research is focused on upper and middle-upper income countries and in the field of behavior change communication (e.g., therapy adherence) and short messaging systems (SMS, e.g., for reminders, or data collection) [30]. The analysis of the economic sustainability of the introduction of mHealth in LMICs is scarce [31]. Another under-investigated issue concerns the quantification of the level of connection between First-Mile hub and Last-Mile hotspot in backward areas like Sub-Saharan Africa [32-33].

This study contributes to overcoming some of the outlined research gaps, deepening the understanding of accessibility to Health Services using mHealth in Uganda (with an extension to other LMIC).

3 Research question

Any innovation is convenient if it generates benefits higher than its implementation costs. As reported in the literature quoted above, mHealth might create profits, this economic aspect is not well defined. Are these savings sufficiently higher than the costs? Healthcare costs consist of internal expenditure (what is needed to produce and deliver health: equipment, staff, consumables) and external expenditure (patients' and families' time and costs, for example, for travel, accommodation, etc.) [31].

Consistently with this background, the paper aims to fill the mentioned literature gap by partially:

1. quantifying the First Mile-Last Mile disconnection, here described as the time-cost for the population to reach a medical center;
2. evaluating the time-cost, and thus the savings, produced by the "mobile point of care" model [34] - an innovative mHealth process to deliver health services;
3. Indicating how to facilitate better and timely access to healthcare for backward populations as well as generate economic and financial savings for all the stakeholders that rotate around the HSC: patients, caregivers (CHW or other), healthcare authorities, etc.

The mHealth "mobile point of care" model [34] is designed to tackle malaria cases in Uganda. It generates savings by the transformation of (non-acute, i.e., chronic) inpatients and outpatients into home-patients. These savings depend on how many patients adopt mHealth. The time-cost decrease in accessing healthcare is one of the main drivers of mHealth adoption [35]. This study consistently considers the demand for mHealth, estimating how many end-users will find such an application more advantageous than the standard healthcare services based on time to access healthcare services. Therefore, the catchment area (i.e., market size) of mHealth services is critical in defining these savings. The method to calculate this area adopts a GIS approach, explained in the methodological section.

The savings can fuel remuneration of the private players that cooperate with public authorities within a Public-Private Partnership (PPP) using Results-Based-Financing (RBF) resources.

The study:

- analyses how geographical mismatch between First- and Last-Mile can be (i) quantified, in terms of time, using a Geographic Information System (GIS); and (ii) converted in economic costs through a cross-sectional analysis to estimate public and private savings in a sample area;
- discusses critical issues such as (i) time to reach First-Mile healthcare services, (ii) role of CHW and (iii) the function of Results-Based Financing (RBF) strategies;
- describes its own limitations, with tips for further research.

4 Methods

In this section, consistently with the research question, we describe the "mobile point of care" model, the geographical method used to determine the market size of mHealth application in a specific study set up, and finally, the methodology and assumptions used to calculate financial savings generated by mHealth.

4.1 "Mobile point of care" model

The "mobile point of care" can digitally network First-Mile hubs and Last-Mile hotspots [36]. This model theorizes that it will be possible to enable a "glocal", i.e., makes global resources virtually available at the local level, diagnosis of malaria.
Figure 1 outlines an example of this mHealth application to manage some HSC criticalities. It aims to improve the connections between Last-Mile hotspots, First-Mile hubs, and national health system resources. The blue arrows represent physical movement (persons and drugs); the red arrows show immaterial flows (data, information, and decisions). The size of the arrows gives a qualitative measure of the increase of streams of people, material, data, news, and decision on the mHealth path compared to the traditional ones, which are partially blocked by barriers (modified from [34]).

INSERT ABOUT HERE FIGURE 1

4.2 Study set up

The study is set up in Uganda, a typical East-Central Africa LMIC, where the "mobile point of care" has been tested. Although health indicators are steadily improving, the performance of Uganda's healthcare system still has ample room to be developed [24, 33].
Uganda is a paradigmatic LMIC because it is affected by the issues that hindrance the First-Mile and Last-Mile connections illustrated in the background. The country has only 6.5 health workers for every 10,000 people [36], far short of the minimum of 23 physicians' ratio for every 10,000 people that the World Health Organization recommends. Moreover, there is a vast urban/rural imbalance in the distribution of health workers that hinders health services delivery in rural areas. Furthermore, not all the approved positions are filled, especially in rural settings [37].
However, Uganda has been implementing results-oriented management (corresponding to RBF) in the public healthcare sector and the decentralization of healthcare workers to local governments [38]. Indeed, the health system in Uganda is based on a hierarchical structure [39]. The Village Health Teams (VHT) are at the base of the healthcare pyramid. They are CHW who mainly deliver health education, preventive, and straightforward therapeutic services. The next levels are represented by Health Center (HC) II (parish level) run by a nurse, and HC III (sub-county level) run by a medical officer and providing some essential diagnostic services. HC IV and district hospitals are run by a medical doctor and can perform some emergency surgeries. At the top of the pyramid, there are regional and national referral hospitals that are equipped to provide all general services and specialized clinics.

4.3 The geographical assessment of disconnection between First- and Last-Mile

A GIS model is developed using QGIS (version 3.4) to determine the level of connection between the First-Mile healthcare hubs and Last-Mile hotspots in the defined geographical setting. The methodology is adapted from the one used to assess the time distance from major cities for the world population [40].
This method determines the geographical position of the (i) First-Mile hubs and the (ii) Last-Mile hotspots. The following step consists of the calculation of a (iii) "friction" surface that defines the cost of moving across a surface on a per-cell basis. Finally, combining these three elements in a GIS is possible to compute the time-cost to cover the distance between each Last-Mile hotspot and the nearest First-Mile hub.
In this study, hospitals and HC IV are defined as Fist-Mile healthcare hubs because they can offer diagnostic laboratory services [41]. HC II and HC III are not included in the analysis due to the

severe limitations and inefficiencies [37]. The geographical position of First-Mile hubs is determined by the authors using websites such as www.google.maps, www.openstreetmap.org, etc. and using a list published by the Ministry of Health (MoH) of Uganda [37].
The Last-Mile hotspots consist of the geographical distribution of the population that requires medical care. For this study, the total population and the community affected by Plasmodium falciparum malaria (Pf malaria) are considered as Last-Mile hotspots. Pf malaria is selected due to its significant diffusion and impact in Uganda and because it represents a case study simple to afford because much data on geographical distribution and costs are available. Moreover, Pf malaria causes very high hospitalization costs.
The geographical position of the total population are calculated from the Worldpop project [42], adjusting to the United Nations estimates for 2015 [43] while of the Ugandans affected by Pf malaria are estimated combining the Pf malaria incidence rate model of MAP project [44, 45] to the total population distribution.
The friction surface is computed combining the following GIS layers (data source in brackets): (i) road networks and navigable water bodies (www.openstreetmap.org), (ii) off-road land cover (Global Land Cover Share database - http://www.fao.org/land-water/land/land-governance/land-resources-planning-toolbox/category/details/en/c/1036355/), (iii) Digital Elevation Model and (iv) derived slope (Advanced Spaceborne Thermal Emission and Reflection Radiometer – ASTER Global Digital Elevation Map https://asterweb.jpl.nasa.gov/gdem.asp).
The combination of these layers defines a "friction" surface, which estimates the time required to cover a cell of 500x500 meters (according to [40]). Finally, combining the position of First-Mile hubs and Last-Mile hotspots with the friction surface, the number of people and Pf malaria cases for the different time-cost range are estimated.

4.4 From time to financial saving

The next step is to calculate how many users will adopt mHealth technologies instead of traveling to a First-Mile center. To do it we need to define the number of cases to which the mHealth model is applicable (i.e., "mHealth penetration rate") and consequently, how many inpatients can be transformed into home patients. Therefore, the study assumes that the population share living at more than one hour of travel from a Frist-Mile hub, defined as "remote users", and affected by Pf malaria, represents the mHealth penetration rate.
The adopted time threshold is used after [32] following the example of neighbouring Rwanda, because the MoH of Uganda does not indicate any limit. Moreover, the study also assumes that the share of inpatients affected by Pf malaria (i.e., "malaria morbidity") in the First-Mile hubs is equal to the ratio of the malaria-infected population. Finally, the study needs to define the effect of early tests and treatment due to the introduction of mHealth. The possibility of prompt diagnosis of Pf malaria through mHealth could transform most of the inpatients or daily outpatients into home-patients. This calculation is based on a study run in Zambia [48] that proved that the early test-and-treat approach in a context of community-based malaria management strategy could lead to a dramatic reduction of inpatient hospitalization (10-fold) and outpatient admissions (up to 20-fold). Therefore, the study assumes that mHealth early test-and-treat produces a 90% drop in malaria-related hospitalization cases (i.e., "early test-and-treat success rate") among the share of the population that adopt mHealth.
Finally, the computation of financial cost for inpatients and outpatients is based on the following secondary data:

- Inpatient admissions, inpatient days and outpatient treatments [46];
- Average costs supported by the national public health service per patient and per category of healthcare hubs [41]. These costs include expenditure for staff, administration, training, medical supplies, pharmaceuticals, equipment, infrastructure, and utilities. Because most patients did not report medical expenses when visiting public facilities, this cost will be neglected in our calculation. Likewise, the cost of medicines will not be considered as it would occur regardless of travel time in case of prescription of the same therapy;

- Private savings based on the average income lost, the cost of transportation, and food [47]. These figures include the costs incurred by the patient plus the accompanying persons.

5 Results

Consistently with the research question, this study mapped 336 First-Mile hubs (147 hospitals and 189 HC IV). The application of the time-cost rules, above described, to First-Mile hubs distribution results in a map with the time cost to the nearest First-Mile hub for each space unit (cell of 500 meters on the side). The time to the closest First-Mile hub for each person can be defined by overlaying the time-cost map with the distribution of the population.
Table 1 summarizes the findings for the whole country and those districts with the highest Pf malaria incidence (more than 20%), and that counts more than 200,000 "remote users" (column i). The table also reports the total population (ii); the average time to the nearest First-Mile hubs (iii); population distribution in four-time ranges (namely less than 30 minutes, between 30 and 60 minutes, between one and two hours, and more than two hours, columns from iv to vii); people affected by Pf malaria (viii); the average time to the nearest healthcare hubs for Pf malaria patients (ix); and, the number of remote users infected by malaria (x).
In Uganda, there are more than 19 million remote users (sum of columns vi and vii, roughly 50% of the population). The districts indicated in Table 1, account for circa six million remote users (about a third of the total) of whom 1.65 are affected by malaria (37%).

Table 1 Population, malaria and time to reach healthcare hubs

INSERT ABOUT HERE TABLE 1

A comprehensive table with all districts is reported in the appendix (Table 3). It highlights the absence of valuable differences between the average times to the nearest First-Mile hubs considering the total population and those affected by Pf malaria. Only seven districts have differences above five minutes, and only for three of them (Bundibugyo, Napak, and Kisoro), the difference is higher than 15 minutes (see table 3 in the appendix). The column iii of table 3 sourced from the map in Figure 2 that shows the average time to the nearest First-Mile hubs by the district.

INSERT ABOUT HERE FIGURE 2

Five districts, namely Kamwenge, Kotido, Kyenjojo, Mpigi, and Kibaale, are characterized by a high Pf malaria incidence and average travel time between 120 and 194 minutes, well above the ideal threshold. Figure 3 shows the number of remote users per district, and how many of them are affected by malaria. The highest incidence of malaria cases, both relative to the district population and in absolute figures, is in the Kibaale district. Consequently, the assessment of the potential economic impact of mHealth is conducted for malaria in Kibaale (in the following subsection).

INSERT ABOUT HERE FIGURE 3

5.1 Impact of mHealth in the Kibaale district

In Kibaale district, there are 377 hospital beds divided among one General Hospital and four HCs IV, which, in 2015, recorded 25,598 inpatients (for 65,297 inpatients days) and 71,600 outpatient admissions [46]. These First-Mile hubs serve 682,280 residents. This study estimates that 308,464 (43%) people live at more than 2 hours, and other 206,286 (30%) at more than one hour from the nearest First-Mile hub. It is worth noticing that the district counts about 213,898 Pf malaria patients, 31.35% of the entire population (i.e., "malaria morbidity" as defined by the method's assumptions). The study calculates that 75.45% of these, namely 160,642, are remote users (i.e.,

"mHealth penetration rate" as defined in the method's assumptions). Table 2 summarizes the actual cost of the healthcare system and estimates the savings by introducing mHealth at the community level (i.e., VHT).
In 2012 [41], the annual budget of healthcare hubs amounts to circa 1.586 million of United States Dollars (USD), 1.392, and 0.194 million, respectively, for inpatient and outpatient treatments (row iv). About half a million USD (row vi) was the share dedicated to caring for malaria patients, considering the malaria morbidity rate in Kibaale. Using the "mHealth penetration rate" and the "early test-and-treat success rate" assumptions, as defined in the methodological section, and calculated above for Kibaale, 5,424 inpatients (for 13,837 of inpatients days) and 15,172 outpatients, out of the 25,598 inpatients and 71,600 outpatients, will no longer need hospitalization (see rows vii and viii). That leads to an overall public saving of more than 300 thousand USD, 21% of total costs for healthcare hubs in Kibaale district.

Table 2 Inpatient versus outpatient costs (in U.S. Dollars, USD) in Kibaale district (https://www.bou.or.ug/bou/collateral/exchange_rates.html)

INSERT ABOUT HERE TABLE 2

In addition to the public costs, there is a hidden private cost incurred by families when a member (especially a child) travels to the hospital (see the second part of Table 2).
Multiplying the decreased number of inpatients and outpatients by the average non-medical costs of hospitalization [47], about 360 thousand USD of private savings emerge. Each family with an inpatient who benefits from the mHealth application could save more than 30 USD. These savings correspond to some 1.5 months of salary in rural areas (20 USD/month) [49], while an outpatient could save about 13 USD.

6 Discussion

This study develops a method to estimate the disconnection between First-Mile hubs and Last-Mile hotspots, a significant HSC bottleneck. Such hindrance can be softened with the introduction of mHealth, which could also trigger savings, contributing to the overall sustainability of the healthcare system. A core question, consistent with the research aim, is whether the expected economic benefits are higher than the costs of mHealth introduction.
The study estimates the amount of such savings for a small region (about 700 thousand inhabitants) of Uganda, a typical African LMIC: private and public sector could save nearly 700 thousand USD. If extended to the entire country, the savings could amount to some tens of millions of USD.
This study, being a theoretical model without an empirical application, cannot report the cost of the specific model proposed. Therefore, scientific literature was used to make an approximation of these expenses . Unfortunately, the cost evaluation of mHealth applications is very scarce. A useful review finds out only 5 studies in LMIC country and is all about SMS reminders for therapy adherence [30], advocating the need for more research in LMICs to understand the impact of different mHealth types. It is noteworthy that there may not be many studies about the cost-utility and -effectiveness of mHealth because there are confidential studies carried out by private companies,
Given this lack of appropriate information, the study compares the cost of two mHealth programs conducted in Uganda and Tanzania, respectively [50-51]. These studies focus on the application of SMS technologies used to communicate health-related information between healthcare hubs and remote patients (in both directions). The findings highlight a cost ranging between 1.5 and 2.5 USD per patient. However, it is a different type of mHealth technology not directly comparable with the proposed model of "mobile point of care".
The failure to demonstrate the value of mHealth is one of the main challenges to widespread adoption of high-performing ICT initiatives [52]; therefore, the economic analysis of mHealth is a critical issue. In the heavily-urbanized OECD countries with generally universal access to

healthcare, most of the investment goes into health management information systems and hospital administration, rather than into the use of mHealth to increase access for underserved populations. It is therefore essential that separate studies will be carried out in LMICs and will need to focus on specific issues, including the introduction of mHealth in remote, rural areas, and the training of CHW to use mHealth technologies.

Generally, costs rise as new and expensive products are adopted by the patient population. It reasonable to think, however, that the introduction of low-cost technologies could reverse this trend, at least as far as delivering health services to poor, underserved populations in both rural and urban areas. Indeed, the cost of mobile phones and other ICT equipment has declined dramatically over the last decade, even as capabilities have increased. Similarly, mobile bandwidth capacity is growing as costs fall. Remote collection and transmission of diagnostic data by CHW to centers with a critical mass of computer programs, skilled technicians, and doctors to interpret the data should be more cost-effective than often unsuccessful efforts to train and deploy an adequate workforce in rural areas.

Noteworthy, the introduction of mHealth could generate collateral benefits that go beyond financial ones. For example, mHealth could also be a catalyst for other technology-driven innovations with direct and indirect socio-economic impact neglected in this study (e.g., prevention and awareness campaigns, trained IT/ICT operators at local community level, cross-sector mobile technologies, etc.). mHealth can also have a long-term impact on the population, increasing the school attendance ratio and working opportunities and, ultimately the income-[53].

In the following subsections, the discussion will focus on two aspects of mHealth penetration: (i) time as a key parameter to determine market size; (ii) how to promote the mHealth acceptance and increase adoption by end-users. Moreover, the study briefly discusses (iii) which financial mechanism can support mHealth development and (iv) study limitation.

6.1 Time of Travel Savings and Costs of Reaching Hospitals

Time of travel is a core parameter of the model because it defines the potential adoption rate of mHealth among the end-users. Its fine-tuning determines the benchmark savings that fuel RBF.

There is not a universally recommended maximum time of travel to a healthcare hub because it depends on several factors that define health services accessibility and use. These factors include "geographic access, resource availability, cultural acceptance, financial affordability, and quality of care" [54]. Such factors can be further divided into [55]:

- Prerequisites: social and personal values and perceptions that induce to use a service;
- Enabling factors to access service (e.g., transportation, money, etc.);
- Health system factors: infrastructure and services offered by the health system.

The analysis highlights that in Uganda, the average travel time is 74.9 minutes, higher than the suggested maximum time-threshold of 60 minutes recommended in neighbouring Rwanda.

Travel distance and time are also an economic burden for patients. The costs incurred by a patient visiting a health facility are:

- Travel expenses (private/public means of transportation), food and beverage costs for patients and accompanying relatives (and accommodation costs for the latter);
- Loss of income (impacted by travel time, waiting time and time of hospitalization);
- Failure of education for school-age children.

For Last-Mile patients with high travel times (who, most often, live in rural areas and have low income), the non-medical hospitalization costs are challenging to manage, and some of them may renounce to medical assistance. There are also other issues: since most cases of pathologies, like malaria, affect children, mothers sometimes cannot take them to the hospital, as this would mean leaving the rest of the family unattended.

Whenever these economic or social costs are unaffordable, or the First-Mile hub is impossible to reach in due time (e.g., due to unmanageable roads during the rainy season), health issues become critical. Untreated brain malaria is just one of many diseases that, in lack of prompt treatment, can have deadly consequences.

In addition to hospitalization, the disconnection between First-Mile hubs and remote users could hinder the proper diagnosis of malaria and other diseases. According to Ugandan MoH, in 2016, there were 15.8 million patients treated for malaria, only 69% of which received laboratory confirmation [36]. There are four to six million more cases of malaria, mostly concentrated in rural areas, with uneasy access to laboratory confirmation. The lack of proper diagnosis leads to inadequate treatment and, thus, complications, higher infection rates, antimalarial drug resistance, and a higher death rate. The introduction of mHealth could increase quality diagnosis among the rural community.

6.2 Last-Mile implementation of mHealth with Village Health Teams

Rural (last-mile) implementation of mHealth is another crucial target of healthcare improvement, consistently with the research question.

VHW already have a vital role in Uganda (called VHT) and, in many other LMIC, acting as a bridge between the communities and the national healthcare system.

Even if they are not healthcare professionals, VHTs are crucial to reducing barriers to healthcare access in peripheral areas [56], because they could answer questions and refer patients correctly. Community-based malaria management through mHealth and VHT can be a disruptive process innovation leading to healthcare delivery improvements and private and public savings. Remuneration and basic health training of VHT are a milestone of mHealth strategies that need to be appropriately deployed in the territory and matched with local patients' needs.

Malaria mobile point-of-care actions (early diagnosis and treatment) could be comparable to what the VHTs do using Rapid Diagnostic Tests (RDT). Mobile microscopy would, however, yield more accurate results, and the technology platform could be used for other healthcare applications. The mHealth could be conveniently deployed through VHT capillary network, which in certain districts covers all villages.

Effective integration of CHW programs into mHealth systems can boost program sustainability and credibility, clarify CHW roles, and foster collaboration between CHWs and higher-level health system actors [11].

6.3 Combining mHealth with Result-Based Financing

Healthcare systems, especially in the LMIC, hardly have the expertise to deploy innovative technologies and so public actors need the cooperation of private players that have such technical ability to ensure supply security efficiently [57].

RBF for health is a cash payment or non-monetary transfer made to a provider, manager, or consumer as an incentive to deliver or use priority healthcare services. Payment is made conditional on measurable actions. RBF is an umbrella term that includes pay-for-performance contracts with healthcare providers; output-based aid; and conditional cash transfers and other demands. This study demonstrates that the savings from the introduction of mHealth even in a single district (*e.g.,* Kibaale) could be significant and could feed RBF mechanism that can boost the private to invest in technological innovation of the HSC.

RBF model should provide a system of economic incentives for private players acting together with public actors or NGOs. This coordination is consistent with a PPP model that is widely used in healthcare [58]. RBF is complementary to mHealth and remunerates digital efforts and convergence to Electronic Health Records. In LMIC, the creation of an information feedback mechanism can move health-care delivery towards results-based practice and help make more efficient use of scarce resources [59].

Although the effectiveness of RBF in LMIC is conflicted [60-61], its application in Northern Uganda has been giving positive results [62]. Further evidence from bordering countries such as Congo and Rwanda shows that experimental RBF-based payment systems have led to rapid qualitative and quantitative improvements in access to healthcare [63-64]. RBF is a valuable tool for donors (and MoH) to guarantee transparency and accountability throughout the HSC that subsidize local healthcare providers for achieving specific benchmarks. Complementary evidence of the effectiveness of RBF for donor-driven initiatives emerges from Benin [65], and for measuring the quality of care in LMIC [66].

6.4 Limitations of the study

This paper has limitations in that it addresses only supply chain applications to the healthcare field on a conceptual basis. No hypotheses were constructed and tested, as the intention of this study was to assess the economic aspects of mHealth application in remote areas. Perhaps the next step should be to test topics raised in this study based on empirical data.

The locations of First-Mile hubs are performed using a list from the Ugandan Ministry of Health (as stated above in the methods) and fine-tuned using Googlemap and Openstreetmap services. These services are limited and slightly unprecise about location but considering the resolution (500 meters) of the friction map, these limitations are acceptable.

The model considers population data in a static way, where migration is not properly captured. The Ugandan case should also include statistics about foreign refugees (such as the South-Sudanese, that are almost 1.5 million people) or nomadic populations, as the Karamajong in the North-Eastern part of the country. This scenario is typical in Africa and beyond and may be a paradigm for the geographical scalability of the model.

Another limitation is concerned with the HSC bottlenecks. The study considers some of these obstacles (last-mile unavailability; SC financing with RBF, etc.) that, however, deserve further interdisciplinary scrutiny.

A further restraint of this paper is that it does not consider cyber-security, IT failures, and privacy issues. Should mHealth become diffused as expected, this would be a significant concern.

7 Conclusions

This study estimates the disconnection between the First-Mile suppliers of healthcare services and the Last-Mile end-users, and the potential public and private savings generated by the introduction of mHealth technologies to fill this disconnection, considering the remote users as the prospective market for mHealth application to diseases like malaria.

The model is tested in Kibaale district (Uganda, which represents a typical LMIC) characterized by high malaria morbidity and significant travel-time to main First-Mile hubs. It is estimated that public savings would be about 20% of the public health budget in the district, amounting to 336 thousand US Dollars (about 1.2 billion Ugandan Shillings at the exchange rate of June 2019). Patient savings, namely other 360 thousand US Dollars, would be 0.25% of Kibaale district GDP.

The findings of this study can inspire new research avenues exploring geographic scalability to other LMICs [67] and vertical integration with different pathologies [68].

Spatial analysis of healthcare basins and efficiency parameters such as the Standard Unit of Output (an indicator used to compare the output volume of hospitals) represents a further research avenue to highlight inefficiencies and suggest interventions.

Further research should focus on expected cost-utility analysis that also includes quality-adjusted life years.

List of Abbreviations

GDP – Gross Domestic Product
GIS – Geographic Information System
HC – Health Center
HSC – Healthcare Supply Chain
ICT – Information and Communication Technology
IT – Information Technology
LMIC – Low-Middle Income Country

MoH – Ministry of Health
NGO – Non-Government Organization
OCR – Optical Character Recognition
Pf - Plasmodium Falciparum
PPP – Public-Private Partnerships
RBF – Results-Based Financing
RDT – Rapid Diagnostic Test
SMS – Short Message Service
TLC – Telecommunication
UGX – Ugandan Shilling
VHT – Village Health Team

Declarations

•Ethics approval and consent to participate

Not applicable.

•Consent for publication

Not applicable.

•Availability of data and material

Data are taken from free sources and then elaborated by the authors.

•Competing interests

The authors declare that they have no competing interests.

•Authors' contributions

RMV and MM conceptualized and designed the study. AL and MM contributed to data collection and analysis. RMV analysed SC bottlenecks and RBF solutions. MM made the geographical study. AL examined time to travel issues. All authors provided final approval and agreed to be accountable for all aspects of the study.

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Figure legend

Figure 1 Disease management process in a mHealth environment

Figure 2 Average time to a healthcare hub for each district (column iv of table 3)

Figure 3 The total amount of remote users, and Pf malaria affected end-users

Appendix

Table 3 Population, average time to the nearest healthcare facility, distribution of the population among times ranges to a healthcare facility and malaria cases

INSERT ABOUT HERE TABLE 3

* * *

Table 1 Population, malaria and time to reach healthcare hubs

	population		**people by time range**				**malaria cases**		
unit	**total**	**average minutes**	**< 30 minutes**	**30-60 minutes**	**60-120 minutes**	**>120 minutes**	**total**	**average minutes**	**> 60 minutes**
UGANDA	**40,144,872**	**74.9**	**10,470,574**	**10,510,613**	**12,706,182**	**6,457,503**	**8,988,846**	**77.1**	**4,514,713**
Kibaale	682,280	131.8	67,276	100,254	206,286	308,464	213,898	130.1	160,642
Mubende	702,337	110	86,834	126,511	256,006	232,986	197,197	111.5	138,490
Arua	901,900	57.1	198,650	348,290	307,967	46,993	220,962	58.3	89,656
Kamwenge	442,401	120.3	22,051	68,715	195,617	156,018	104,212	126.9	83,011
Luwero	579,159	84.3	116,839	112,198	235,893	114,229	124,457	89.1	78,310
Kyenjojo	440,331	141.2	26,948	64,776	108,233	240,374	122,544	141.6	97,408
Kamuli	608,478	71.2	103,135	161,720	270,694	72,929	164,109	70	89,679
Tororo	637,173	65.7	139,263	182,784	246,796	68,330	238,045	66.3	118,463
Hoima	567,136	74.9	111,553	146,306	210,902	98,375	164,576	75.4	89,886
Yumbe	419,407	95.8	50,451	94,183	193,191	81,582	107,389	94.7	70,179

Kayunga	495,563	76.8	102,128	134,284	169,994	89,157	107,899	82.2	61,491
Luuka	311,128	94.2	15,761	39,651	196,459	59,257	86,863	96.1	71,444
Buyende	321,151	93.2	25,852	51,884	162,063	81,352	99,403	93.9	76,260
Paliisa	430,765	75.9	81,414	116,026	180,700	52,625	155,234	74	81,894
Mpigi	314,745	107.8	42,503	44,294	112,750	115,198	64,212	109.1	47,114
Kabarole	585,324	63	134,741	234,190	175,175	41,218	129,722	56.6	46,204
Namutumba	281,633	114.2	16,849	48,529	117,353	98,902	102,298	114.2	78,483
Moyo	319,565	103.5	48,466	54,927	112,303	103,869	71,800	105.1	48,428
Mityana	445,467	68	119,338	112,472	145,735	67,922	109,865	68.9	53,618
Iganga	607,387	48.9	193,534	201,867	199,013	12,973	183,297	50.1	66,171
...	...	...	...	...	...	...	...	...	...

Table 2 Inpatient versus outpatient costs in Kibaale district.

Kibaale district	**Beds**	**Inpatient days**	**Admissions**	**OPD***	**Inpatient day cost (USD)**	**Outpatient cost (USD)**	**Total Inpatients' costs (USD)**	**Total Outpatients' costs (USD)**
District Hospital (DH)	160	44,101		21,917	11.31	4.11	498,893	90,070
Total HC IV	217	21,196		49,683	42.16	2.09	893,577	103,840
DH + HC IV	377	65,297	25,598	71,600			1,392,470	193,910
					rate			
Malaria morbidity		20,471	8,025	22,447	31.35%		436,546	60,792
mHealth penetration rate		15,374	6,027	16,858	75.10%			
early test-treat success rate		13,837	5,424	15,172	90.00%			
TOTAL PUBLIC SAVINGS							**336,160**	
PRIVATE COSTS:	**cost USD [47 WWB 2016]**	**Savings**					**Inpatients' savings (USD)**	**Outpatients' savings (USD)**
Transport (per patient)	1.47		7,967	22,283			164,997	194,471
Food (per day)	1.42	19,583		21,473				
Lost income (per day)	9.93	137,448		150,715				
Savings (USD per capita)							30.42	12.82

TOTAL PRIVATE SAVINGS	**359,468**	

Table 3 Population, average time to the nearest healthcare facility, distribution of the population among times ranges to a healthcare facility and malaria cases

unit	total	average minutes	< 30 minutes	30-60 minutes	60-120 minutes	> 120 minutes	total	average minutes	> 60 minutes
UGANDA	**40,144,872**	**74.9**	**10,470,574**	**10,510,613**	**12,706,182**	**6,457,503**	**8,988,846**	**77.1**	**4,514,713**
Abim	89,020	129.5	10,793	20,325	19,347	38,555	20,191	132.1	13,257
Adjumani	304,437	77.6	58,915	90,455	108,965	46,102	74,912	82.5	38,672
Agago	308,890	74.1	54,029	104,033	97,093	53,735	72,458	76.5	36,843
Alebtong	243,002	68.9	42,713	84,490	82,305	33,494	70,917	67.5	33,006
Amolatar	127,715	80.9	20,890	22,988	56,553	27,284	39,370	80.7	25,711
Amudat	104,957	395.2	3,135	1,707	5,941	94,174	20,574	404.7	19,747
Amuria	294,659	73.5	54,757	94,791	97,091	48,020	71,654	73.7	35,419
Amuru	212,027	107.4	18,396	36,704	105,518	51,409	70,977	111.5	53,612
Apac	381,600	66.7	95,733	116,083	112,343	57,441	130,185	66.1	57,292
Arua	901,900	57.1	198,650	348,290	307,967	46,993	220,962	58.3	89,656
Bududa	207,702	81.0	23,474	53,570	97,688	32,970	67,633	78.8	41,604
Budaka	228,358	77.2	23,174	71,330	103,118	30,736	89,931	77.3	53,078
Bugiri	315,269	84.7	26,056	79,341	145,121	64,751	106,243	84.6	70,834
Buhweju	140,430	59.0	38,607	50,661	37,382	13,780	17,155	57.6	5,971
Buikwe	558,383	56.9	138,174	228,137	150,202	41,870	84,696	59.4	31,656
Bukedea	204,397	49.0	59,278	91,309	48,405	5,405	67,928	48.4	17,785
Bukomansimbi	234,573	91.4	11,680	41,799	130,950	50,144	58,538	92.8	45,449
Bukwo	69,510	61.6	18,603	20,634	24,707	5,566	10,402	59.2	4,076
Bulambuli	140,312	126.3	0	5,780	79,708	54,824	40,934	125.2	39,245
Buliisa	104,696	77.2	15,159	26,890	47,426	15,221	26,959	78.7	16,427
Bundibugyo	249,261	85.7	67,848	76,523	65,197	39,693	55,507	71.5	22,153
Bushenyi	346,461	57.1	80,693	119,823	126,534	19,411	51,713	56.5	21,489
Busia	204,856	51.2	56,697	76,795	62,950	8,414	68,610	50.8	23,487
Butaleja	264,948	92.6	52,507	66,835	73,805	71,801	103,184	92.8	56,662
Butambala	145,494	143.4	6,848	9,986	52,027	76,633	34,345	147.4	30,519
Buvuma	67,341	134.0	162	466	29,831	36,882	12,972	133.0	12,854
Buyende	321,151	93.2	25,852	51,884	162,063	81,352	99,403	93.9	76,260
Dokolo	200,733	66.0	40,620	66,715	68,442	24,956	58,688	65.6	27,087
Gomba	224,181	134.8	15,791	24,930	50,189	133,271	61,050	132.4	49,284
Gulu	490,741	42.3	220,388	166,134	80,534	23,685	157,426	45.0	37,001
Hoima	567,136	74.9	111,553	146,306	210,902	98,375	164,576	75.4	89,886

Ibanda	310,325	57.7	57,123	140,576	94,516	18,110	57,998	56.4	20,401
Iganga	607,387	48.9	193,534	201,867	199,013	12,973	183,297	50.1	66,171
Isingiro	505,543	89.5	56,886	133,525	198,715	116,417	45,725	88.5	27,566
Jinja	663,003	40.1	328,062	172,830	135,250	26,861	113,462	44.6	32,450
Kaabong	644,067	212.3	57,223	68,129	138,908	379,807	73,223	218.2	58,308
Kabale	755,931	68.2	195,085	208,798	233,444	118,604	3,307	57.2	1,228
Kabarole	585,324	63.0	134,741	234,190	175,175	41,218	129,722	56.6	46,204
Kaberamaido	219,177	49.8	80,254	76,362	47,099	15,462	64,849	49.6	18,376
Kalangala	50,328	92.8	5,079	5,269	26,420	13,560	8,772	93.0	6,957
Kaliro	259,852	102.3	23,630	36,912	114,140	85,170	86,408	101.9	65,979
Kalungu	270,336	79.3	45,007	70,113	106,291	48,925	64,561	80.8	37,717
Kampala	2,408,384	11.1	2,365,609	42,775	0	0	229,251	11.5	0
Kamuli	608,478	71.2	103,135	161,720	270,694	72,929	164,109	70.0	89,679
Kamwenge	442,401	120.3	22,051	68,715	195,617	156,018	104,212	126.9	83,011
Kanungu	343,124	82.5	50,229	87,337	126,158	79,400	32,435	84.1	20,287
Kapchorwa	116,279	78.3	22,906	21,871	45,363	26,139	28,438	81.3	18,311
Kasese	842,719	72.9	214,999	225,736	263,764	138,220	121,709	69.6	58,117
Katakwi	199,174	80.6	48,842	55,238	49,903	45,191	43,800	79.8	20,741
Kayunga	495,563	76.8	102,128	134,284	169,994	89,157	107,899	82.2	61,491
Kibaale	682,280	131.8	67,276	100,254	206,286	308,464	213,898	130.1	160,642
Kiboga	180,218	56.6	51,679	63,063	51,749	13,727	49,493	56.2	17,782
Kibuku	216,112	69.5	28,920	70,186	100,539	16,467	84,223	69.3	45,487
Kiruhura	325,194	86.4	42,427	82,863	137,922	61,982	63,531	86.9	39,962
Kiryandongo	314,760	71.8	35,631	99,894	149,928	29,307	101,218	73.1	58,356
Kisoro	360,830	78.6	69,855	105,988	132,347	52,640	3,597	155.7	3,039
Kitgum	271,040	64.8	87,172	80,002	72,427	31,439	63,817	64.8	24,832
Koboko	211,640	58.3	58,653	50,840	92,840	9,307	55,519	59.7	27,757
Kole	281,919	57.0	60,560	108,206	99,742	13,411	97,182	57.1	39,097
Kotido	250,699	168.5	26,375	36,936	75,362	112,026	36,253	180.5	27,777
Kumi	277,853	51.3	88,678	100,080	80,065	9,030	85,459	49.9	26,014
Kween	113,185	84.8	10,723	30,541	47,320	24,601	16,452	78.3	9,390
Kyakwanzi	199,903	106.6	17,596	60,128	61,014	61,165	59,755	105.4	36,362
Kyegegwa	182,954	105.7	29,886	44,146	52,698	56,224	53,821	105.3	31,778
Kyenjojo	440,331	141.2	26,948	64,776	108,233	240,374	122,544	141.6	97,408
Lamwo	192,774	105.5	23,460	43,571	72,492	53,251	50,652	110.0	34,032
Lira	418,575	38.4	212,800	120,361	76,374	9,040	131,062	39.7	27,909
Luuka	311,128	94.2	15,761	39,651	196,459	59,257	86,863	96.1	71,444

Luwero	579,159	84.3	116,839	112,198	235,893	114,229	124,457	89.1	78,310
Lwengo	350,008	56.8	101,583	122,044	92,172	34,209	63,302	55.6	21,782
Lyantonde	111,587	72.1	19,581	26,858	48,076	17,072	19,892	73.9	12,142
Manafwa	437,107	54.4	91,347	185,219	150,384	10,157	142,127	53.4	50,144
Maracha	225,284	69.2	16,247	70,839	129,029	9,169	59,126	69.0	36,113
Masaka	439,741	83.6	113,040	121,736	104,006	100,959	89,999	85.8	43,778
Masindi	351,577	84.4	70,367	83,854	123,188	74,168	97,558	84.7	54,578
Mayuge	326,215	72.2	33,522	99,867	165,366	27,460	81,652	71.8	47,782
Mbale	558,802	40.5	260,434	162,098	127,132	9,138	188,942	40.8	46,626
Mbarara	603,840	61.8	175,820	168,898	195,549	63,573	69,955	61.5	29,619
Mitooma	271,137	74.3	39,302	88,762	99,283	43,790	39,922	73.1	20,576
Mityana	445,467	68.0	119,338	112,472	145,735	67,922	109,865	68.9	53,618
Moroto	129,630	159.6	24,266	23,630	31,732	50,002	16,232	167.7	10,754
Moyo	319,565	103.5	48,466	54,927	112,303	103,869	71,800	105.1	48,428
Mpigi	314,745	107.8	42,503	44,294	112,750	115,198	64,212	109.1	47,114
Mubende	702,337	110.0	86,834	126,511	256,006	232,986	197,197	111.5	138,490
Mukono	714,348	81.9	116,459	142,740	312,586	142,563	116,837	85.2	78,143
Nakapiripirit	151,863	143.3	19,065	30,769	39,537	62,492	28,892	142.8	19,588
Nakaseke	230,877	72.8	60,996	75,251	59,868	34,762	58,840	74.5	24,567
Nakasongola	212,932	127.4	8,496	23,964	79,124	101,348	58,553	127.7	50,025
Namayingo	125,354	93.6	11,546	25,059	54,955	33,794	36,476	89.7	24,932
Namutumba	281,633	114.2	16,849	48,529	117,353	98,902	102,298	114.2	78,483
Napak	178,949	165.2	8,226	40,436	49,279	81,008	27,632	179.4	20,835
Nebbi	420,287	58.6	90,691	148,379	159,212	22,005	105,841	59.3	46,103
Ngora	171,601	80.6	22,848	50,820	69,859	28,074	49,818	78.8	27,352
Ntoroko	84,973	148.4	10,540	18,267	17,394	38,772	19,472	145.6	12,705
Ntungamo	639,342	69.4	98,813	193,712	290,228	56,589	56,802	68.4	30,621
Nwoya	65,651	70.7	20,378	21,450	12,252	11,571	22,158	72.3	8,300
Otuke	79,718	74.3	18,032	24,104	22,653	14,929	20,200	75.4	9,621
Oyam	408,354	43.9	152,062	158,259	91,753	6,280	144,925	43.9	34,767
Pader	238,758	82.1	37,241	71,224	88,545	41,748	67,836	85.7	38,498
Paliisa	430,765	75.9	81,414	116,026	180,700	52,625	155,234	74.0	81,894
Rakai	663,151	77.2	91,673	211,154	266,663	93,661	111,273	75.5	59,613
Rubirizi	161,852	76.5	16,024	45,100	79,404	21,324	27,502	77.1	17,226
Rukungiri	462,965	55.5	91,748	194,337	159,261	17,619	49,996	55.2	19,102
Sembabule	302,809	69.5	62,831	88,214	112,004	39,760	72,432	69.4	35,912
Serere	289,836	58.5	78,937	109,425	75,082	26,392	87,091	57.8	29,919

Sheema	302,038	55.8	77,382	121,267	81,924	21,465	42,148	53.6	13,790
Sironko	270,911	53.2	54,994	121,067	89,067	5,783	87,422	51.9	29,130
Soroti	325,783	42.1	130,624	125,157	63,343	6,659	86,917	42.8	18,989
Tororo	637,173	65.7	139,263	182,784	246,796	68,330	238,045	66.3	118,463
Wakiso	1,614,935	41.1	863,505	440,043	223,824	87,563	226,236	48.1	57,266
Yumbe	419,407	95.8	50,451	94,183	193,191	81,582	107,389	94.7	70,179
Zombo	279,476	60.0	27,899	141,239	97,156	13,182	75,734	60.6	30,757

Figure 1 Disease management process in a m-Health environment

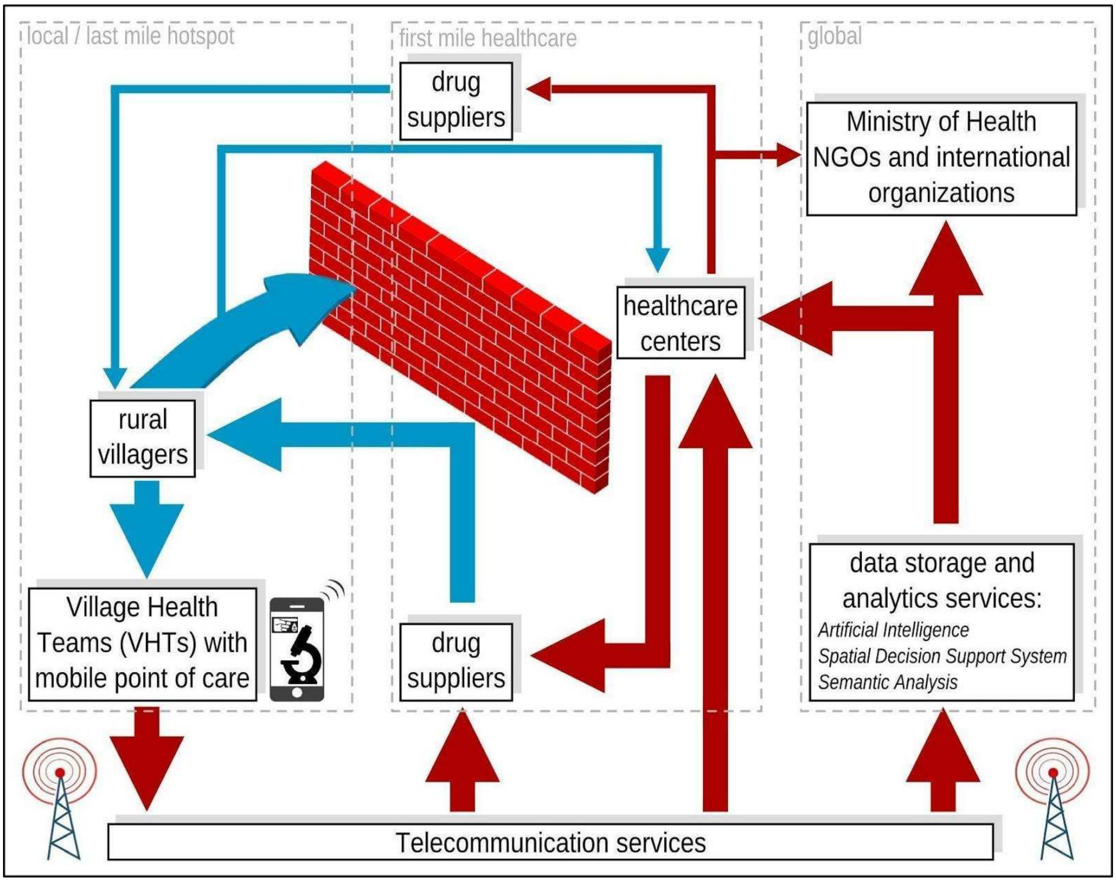

Figure 2 Average time to a healthcare hub for each district

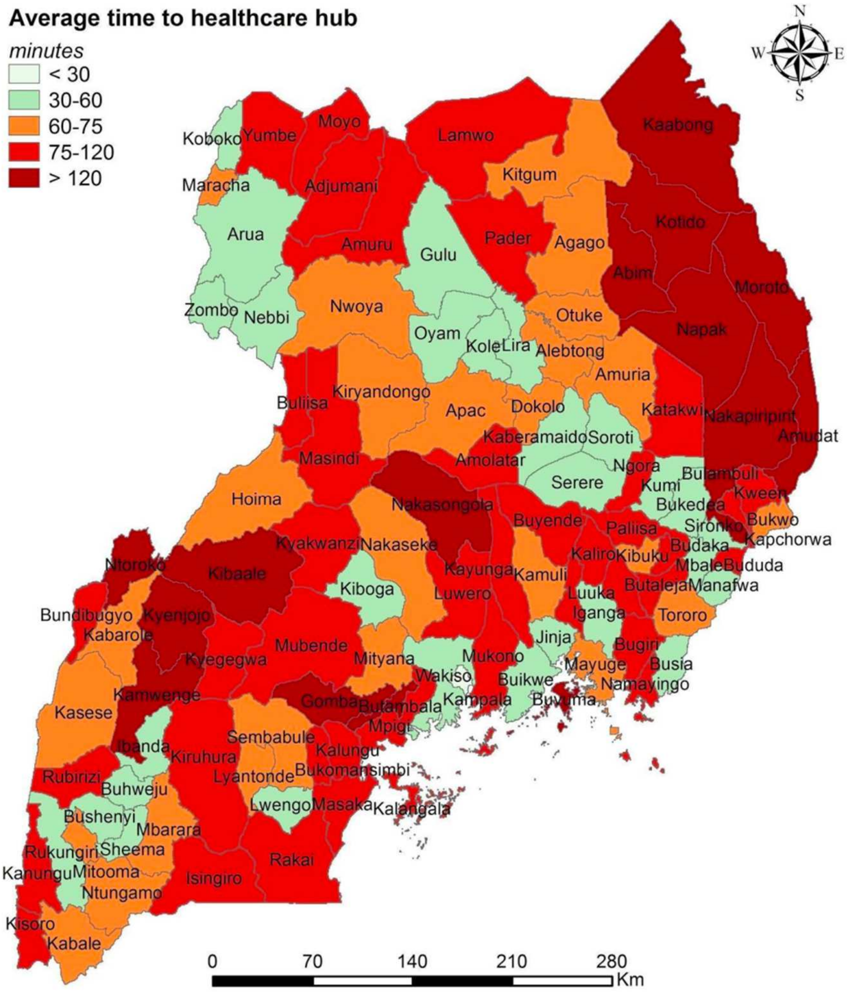

Figure 3 The total amount of remote users, and Pf malaria affected end-users