

**VacSeen: Semantically Enriched Automatic
Identification and Data Capture for Improved
Vaccine Logistics**

by

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Submitted to the Institute for Data, Systems, and Society
in partial fulfillment of the requirements for the degrees of

Master of Science in Technology and Policy Program

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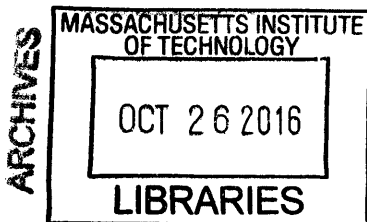
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Abstract

Vaccines are globally recognized as a critical public health intervention. Routine immunization coverage in large parts of the developing world is around 80%. Technology and policy initiatives are presently underway to improve vaccine access in such countries. Efforts to deploy AIDC technologies, such as barcodes, on vaccine packaging in developing countries are currently ongoing under the aegis of the 'Decade of Vaccines' initiative by key stakeholders. Such a scenario presents an opportunity to evaluate novel approaches for enhancing vaccine access. In this thesis I report the development of VacSeen, a Semantic Web technology-enabled platform for improving vaccine access in developing countries. Furthermore, I report results of evaluation of a suite of constituent software and hardware tools pertaining to facilitating equitable vaccine access in resource-constrained settings through data linkage and temperature sensing. I subsequently discuss the value of such linkage and approaches to implementation using concepts from technology, policy, and systems analysis.

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There are several people whom I am grateful to for enabling me to live my dream of studying at MIT. First of all, I am immensely grateful to Professor Sanjay Sarma for accepting me at MIT Auto ID Labs and extending to me the freedom to study a topic I deeply care about. In him, I have found an inspiration and mentor for life. My pursuit to evolve into one of world's best semantic web technologists per his advice will continue long after I graduate.

I am fortunate to have a family that lets me dream and believes in me to accomplish them. Words cannot do justice to my indebtedness to my mother for everything she has been through to help me get this far. I will hence refrain from making an attempt. What I study was one of the last things that piqued my late father's interest as his health gradually declined. "Even how sweets are made is technology" was his remark as I explained my courses. I hope I have his blessings in my efforts to help make the world better, and hopefully sweeter. My better half put up with all of my myriad versions as I devoted myself utterly to graduate education. I wouldn't be here without her care, encouragement, and support.

It was my privilege to work with exceptional peers at the lab and collaborators. I learned as much technology as humility and ability to enjoy solving difficult problems from them. Rahul, Isaac, Stephen, Sumeet, Josh, Dylan, Pranay, Jason, and Eric, my peers at Auto ID Labs, will always be dear friends and guides for me. I have much to thank Dr. Monika Solanki, my collaborator, for. Her guidance and technical expertise were invaluable help when I stumbled with no answers in sight.

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Chapter 1

Introduction

1.1 Preamble

I write this thesis with a sense of satisfaction of studying an issue of deep interest to me and the motivation to continue working on it going forward. It is common knowledge that equitable access to vaccines globally is not yet a realized goal and one that needs to be high on the agenda of those who strive to promote and secure human health. While focusing on what needs to be done, one can lose sight of how far the vaccine access community has come in addressing this challenge. It is a tribute to the undying efforts of scores of dedicated personnel, some of whom I had the privilege of interacting with over the course of my research, that immunization coverage rates in much of the developing world are over 80% [47].

The technologies discussed in the thesis and used to develop the described solution have significant structural and functional advantages over legacy approaches that are currently in use for information systems pertaining to immunization. The tools and solutions described here are aimed at complementing, instead of disrupting, the existing set-up. The amenability of a technological solution to seamless integration with current infrastructure is critical for its adoption in the context of global health. One hopes that the solutions detailed in this thesis find widespread application in the field.

I have made my best effort to accurately report the work I have performed both

individually and in collaboration. It is possible, however, that I have erred in filtering out some of the mistakes that I made along the way from creeping into this thesis. I assume all responsibility for any errors that may be present in this document despite my best effort to weed them out.

1.1.1 Context

This thesis reports the research I undertook at Next Generation Auto ID Labs at MIT under the supervision of Professor Sanjay Sarma. The focus of my research was improving access to vaccines at the last mile in developing countries by improving software and hardware associated with tracing vaccines and ensuring their temperature integrity. The culmination of my work is VacSeen, a software and hardware platform for tracing vaccines and sensing temperature excursion beyond specified thresholds. My research was anchored to a personal interest to study the issue and contribute to solving it, and as a response to ever-increasing focus within the global health community to catalyze actions that enable ubiquitous access to immunization.

1.2 Description of VacSeen

VacSeen is a platform comprising a suite of technologies for improving vaccine access through improved last mile operations in developing countries. It addresses two key challenges in ensuring access to essential vaccines in such settings as described below:

1. *Siloed Data and Consequent Lack of Interoperability*

As described in Section 1.5.1, data interoperability has not been as much of a focus for the vaccine access community as electronic data capture. VacSeen addresses this issue by application of Semantic Web technologies for linking disparate data. The platform enables informed decision-making with regards to last mile operations of immunization by facilitating both statistical and logic-based analytical operations on connected data.

2. *Lack of Low-Cost Digital Temperature Sensing*

Most of the vaccines used in routine immunization are susceptible to damage due to breach of high- and/or low- temperature thresholds. VacSeen seeks to address the challenge of last mile sensing of temperature breaches through a low-cost RFID-based sensor that can electronically and visually detect excursions beyond upper and lower temperature bounds. The sensor, currently under development, is being fabricated using low-cost and readily available components.

1.3 Thesis Structure

This thesis is divided into 5 chapters. Chapter 1 establishes the context of the project, offers an overview of the state of vaccine access, and synthesizes the topics that underlie the premise of the project. Chapter 2 reports the survey of literature relevant to the project. The survey is categorized as per the key themes of the project. Chapter 3 offers details of the development of the VacSeen platform through dedicated sections to constituent software and hardware components. Chapter 4 replicates the structure of Chapter 3 and reports the findings of the project. Chapter 5 reports the synthesis of knowledge through the project and lays down additional findings to guide the implementation of the platform.

1.4 State of Vaccine Access

Vaccines are recognized as one of the most critical public health interventions globally [3]. In fact, vaccination is second only to providing clean water in terms of impact on saving lives and promoting good health [40]. Yet, it is a matter of grave concern that not every child in the world has equal access to essential vaccines. Immunization rates in several developing countries are often sub-optimal at around 80% [47]. This stark reality persists despite significant improvements in the socio-technical system underlying universal immunization over the last two decades.

The marked increase in immunization coverage in large parts of the developing world is anchored to three factors. First, the stakeholders of the global immuniza-

tion ecosystem have invested concerted efforts into establishing dedicated intervention mechanisms and zealously tracking outcomes. These efforts are evidenced through developments such as the establishment of Global Alliance for Vaccines and Immunization (GAVI), declaration of the timeframe between 2011 and 2020 as the 'Decade of Vaccines'¹, and identification of immunization as a key goal by agencies such as the Bill and Melinda Gates Foundation (Gates Foundation) and Program for Appropriate Technologies in Health (PATH).

The second factor is the emergence of universal immunization as a policy prerogative for national and local governments in several developing countries. This factor has played a singularly effective role in democratizing vaccine access by facilitating inflow of funds into mass immunization programs, partnerships with international donors and implementation partners, and continuity in expansion of immunization services.

The third key factor underlying the renewed thrust on routine immunization in the last few years is the permeation and standardization of Information and Communication Technologies (ICT) in vaccine logistics. Vaccine access, much like other aspects of global health, has typically been a ICT-naive sector. However, the mobile revolution coupled with steady establishment of supporting infrastructure in developing countries has catalyzed an unprecedented adoption of ICT for not only rendering vaccine logistics more efficient but also effectively linking the Logistics Information Management System (LMIS) with Health Management Information System (HMIS). The increasing adoption of platforms such as eLMIS and DHIS2, in addition of emergence of dedicated technology firms such as Dimagi and VaxTrac bears testimony to adoption and standardization of ICT in the domain.

The above-mentioned factors represent progress on technology and policy fronts; however, it is imperative to note that significant challenges persist pertaining to vaccine access in developing countries. While the discipline-specific challenges pertaining to technology—data capture and integration in the field, establishing technology stan-

¹http://www.who.int/immunization/global_vaccine_action_plan/DoV_GVAP_2012_2020/en/

dards, and unification of data—and policy—policy harmonization at the global level, ensuring policy continuity through flux in funding, and regulatory push for technology adoption—have been widely characterized and addressed in literature, I found limited evidence of efforts to address the issue of vaccine access holistically. The design of an effective solution necessitates further characterization of the issue.

Subdued vaccine access in developing countries is a multi- dimensional and -scale problem. On one hand, a key focus of interventions is equipping countries to efficiently and timely procure, store, distribute, and administer the vaccines. The spectrum of solutions in this regard includes ensuring continuity of funds, operation of the cold chain, training personnel in vaccine handling and administration, and ensuring robust surveillance for adverse event monitoring and treatment. For an intervention aimed at one of these problems to be successful in such resource-constrained settings, its coherence to others that address allied problems is critical.

On the other hand, interventions that aim to improve vaccine access in developing countries need to be contextualized in terms of scale. Suboptimal vaccine access can be considered to be both a local as well as global problem, particularly from the standpoint of implementation of technological interventions. The global health space is replete with instances of the inability of technology-based solutions to scale-up. Tomlinson *et al.* report the lack of evidence-based scale up of mHealth interventions and identify the "scatter-shot approach" as a dampner to optimal utilization of underlying technology [46]. WHO has reported that interoperability between stakeholders is critical for the success of pilot e-Health programs as its absence often results in high cost and inefficiencies during scale-up ².

It can be ascertained from the above-mentioned facts that the state of access to essential vaccines, despite improvements in the recent past, is far from ideal in developing countries. The challenges underlying the subdued coverage are technical, political, and systemic in nature. An effective approach aimed at improving the ground situation thus needs to span multiple axes.

²<http://www.who.int/bulletin/volumes/90/5/12-040512/en/>

1.5 Motivations

The low coverage in developing countries is, in part, due to the near-absent visibility into the movement of vaccines in the supply chain. The lack of visibility is particularly high at the last mile where the likelihood of product damage and wastage is the highest. The dearth of such information gives rise to issues on both demand and supply sides. From the point of view of the former, in-country supply chains often find it difficult to manage stocks reliably which in turn leads to product wastage. A recent example of such wastage is from Pakistan where donated pentavalent vaccines worth USD 3.7 million were wasted due to improper storage³. The issue of sub-optimal stock management is getting accentuated as the total vaccine consumption per child increases by up to 143% with the introduction of new vaccines into routine immunization schedules [48].

The supply chains of developing countries are not equipped to handle the higher volume as depicted in figure 1-1 [48]. In addition, the information void at the point of vaccine administration renders the surveillance of vaccine-related adverse events, a critical function of health systems, difficult⁴. The inability to accurately link vaccines to their recipients can result in under-reporting of such adverse events⁴. Another attendant issue with subpar detection of vaccine consumption is the inability of buyers—typically governments and international funding agencies—to issue guidelines for tenders that reflect the needs on the ground accurately such as time to product expiration⁴. The availability of such data will enable both buyers and vaccine manufacturers to exercise flexibility in price and volume negotiations.

From the sellers' perspective, the availability of last mile vaccine consumption data is increasingly gaining in importance because of regulatory pressure as well as commercial implications. The absence of data from the last mile limits the ability of sellers to effectively forecast demand and resolve issues associated with counterfeiting and product diversion. Unlike in the past, governments are increasingly holding the manufacturers accountable for ensuring traceability of vaccines. For instance,

³<http://www.reuters.com/article/us-pakistan-vaccine-idUSKBNOLY19920150302>

⁴Dr. Jos Vandelaer, Immunization Expert, personal communication, March 17, 2016

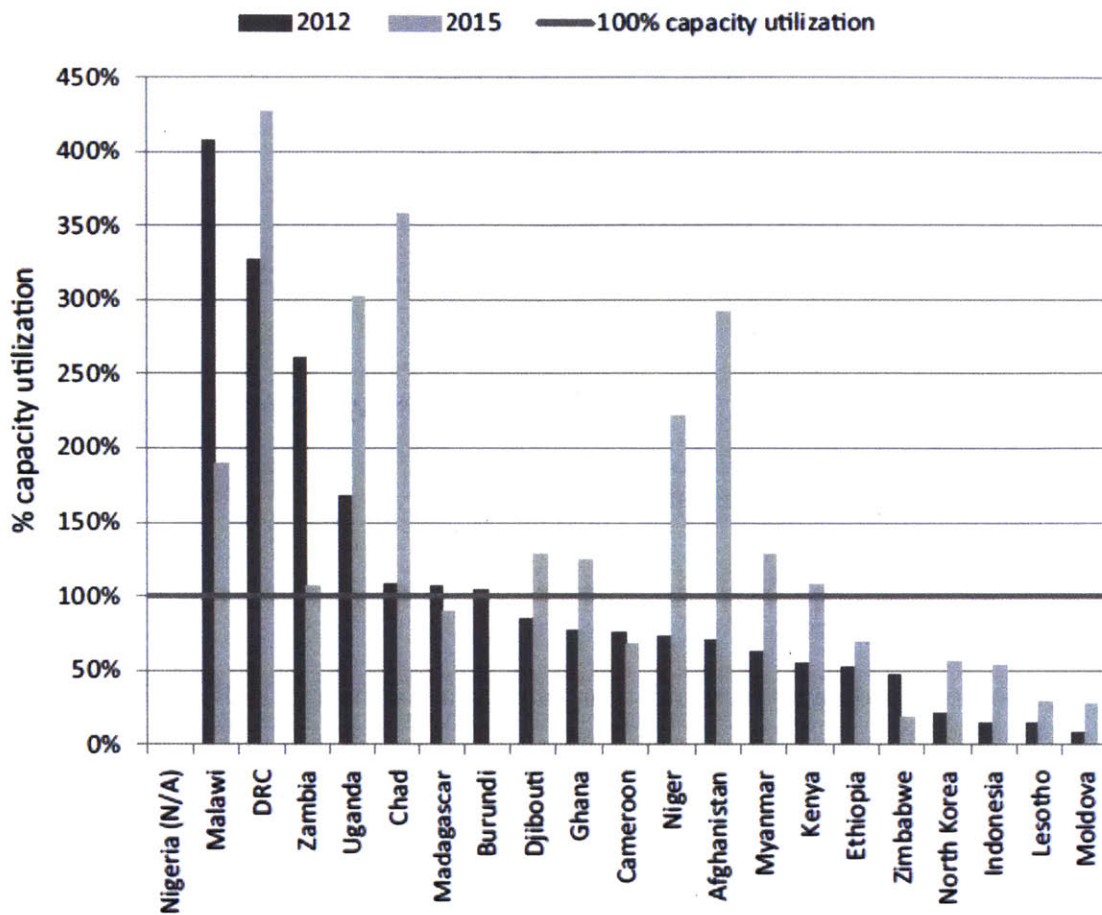


Figure 1-1: Percent of National Store Occupied by Vaccine in 20 GAVI-Eligible Countries (Actual[2012] and Planned[2015])

European Union has set a deadline of 2018 for serialization of drugs for enhanced traceability. Similar norms have been instituted in several other countries such as Brazil, Jordan, Mexico, and Ukraine ⁵.

In addition, vaccines for routine immunization, typically not considered an attractive business proposition by sellers because of their low prices, are increasingly witnessing the strengthening of their business case through increase in prices of the newer vaccines. Brenzel reports progressive increase in cost of immunization per child with the addition of new vaccines as represented in Fig 1-2 [12].

In such a scenario, the ability to determine consumption of vaccines is likely to enable the sellers to demonstrate regulatory compliance as well as inculcate greater

⁵<http://www.pharmaserialisation.com/serialisation-deadlines--printable-worldmap-mc>

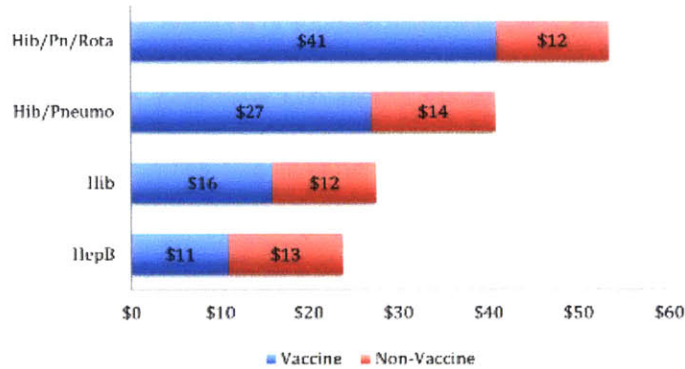


Figure 1-2: Effect of New Vaccines on Cost per Infant (n=243)

efficiency in forecasting and meeting demand.

1.5.1 Technology

Inculcation of Automatic Identification and Data Capture (AIDC) technologies into immunization ecosystem is a priority across countries. Several countries have issued directives to vaccine manufacturers to include barcodes on vaccine packaging^{6,7} [6]. However, the adoption of such basic technologies has been historically lackluster in developing countries because of issues such as paucity or high cost of supporting infrastructure, need for skilled labor for operation, and lack of stakeholder engagement [personal communication, 2014]. With the advent of personal computing devices and improvements in wireless communication networks, the opportunity to use these AIDC technologies presents itself again. Members of the Vaccine Packaging and Presentation Advisory Group (VPPAG), a joint effort by the major stakeholders in vaccine access, have launched a multi-stakeholder project in Tanzania to implement barcodes on vaccine packaging representing a renewed global effort to promote AIDC technologies in the vaccine supply chain [45]. For this project to succeed, demonstration of the additional value generated by deployment of AIDC technologies is critical. A key step to doing so is to provide vaccine consumption data, especially for the last mile of the supply chain.

⁶<http://www.sidley.com/news/major-vaccine-standards-change-in-china-01-24-2011>

⁷<http://www.securindustry.com/turkey-sets-short-timeframe-for-pedigree-system/s15/a29/>

In addition, the linkage of consumption to product details is highly desirable in the context of global health. This is reflected in one of the conclusions drawn by VPPAG in its meeting in 2013:

"Online databases need to be established where barcode information can be retrieved (for example, for a logistician to find out that the item he has just scanned is a box of 25 vials of measles, mumps, and rubella vaccine that needs to be stored between 2 °C to 8 °C). An existing WHO vaccine product database can potentially be adapted to serve this purpose." [45]

Legacy IT technologies, such as relational databases, have intrinsic limitations in representing such linkages as I elucidate subsequently in the thesis.

The generation of end-to-end visibility into vaccine movement through the supply chain, as well as linkage between diverse datasets, is currently not possible in developing countries due to challenges such as disparities in communication technology, non-standardized data storage, and entrapment of data in silos. As a result, the interoperability of logistical and health information management systems is largely unrealized. Numerous commercial entities are presently engaged in developing technology-based solutions for tracking vaccines in developing countries^{8,9,10}. Despite improved information flow, issues about interoperability and at-scale last mile tracking continue to persist.

In such a scenario, the pursuit of technologies that enable linkage of siloed data with minimal disruption of existing information systems is important. Concurrently, the amenability of the considered technologies to be scalable, stable, cost-effective, and learner-friendly is necessitated by the pragmatic considerations of deploying them in resource-constrained settings. Several firms have demonstrated success in using recent technologies to create information systems for improving tracking of vaccines deep into the supply chain. VillageReach's openLMIS, Dimagi's CommCare, VaxTrac's mobile vaccine registry system, and Logistimo's suite of supply chain products

⁸<http://vaxtrac.com/>

⁹<http://www.logistimo.com/products>

¹⁰<http://www.path.org/vaccineresources/supply-chain-and-logistics-systems.php>

are cases in point^{11,12,8,9}. However, these organizations have primarily focused on data capture. The issue of data interoperability remaining largely unresolved.

Linked Data and Semantic Web technologies present an opportunity to create abstraction layers over existing data in order to bridge them. However, the nascence of the technologies indicate risks associated with production-scale deployment. In such a scenario, the need for data interoperability in immunization information systems and the recent emergence of open source tools for creation and consumption of Linked Data served as motivation for our evaluation of the technology as part of our project.

The delivery of vaccines on time needs to be complemented with ensuring that their integrity and potency is not compromised during transportation and storage. A major cause of loss of potency and integrity is temperature-induced damage. For instance, it was suspected that differential exposure to freezing temperatures in rural and urban areas resulted in attendant difference in potency (71.4% and 94.6% respectively) of Hepatitis B vaccine in Mongolia [17,18]. Coupling of AIDC technologies for product tracking and temperature sensing is an attractive proposition in such a scenario because of the availability and maturation of standards, industrial experience in deploying such technologies at scale in other sectors, and decrease in the cost of deployment over time.

1.5.2 Policy

It is apparent that inequitable vaccine access is not a mere technological problem. The suite of legacy ICT technologies are, in principle, adequate for the development of information systems that can enhance the efficiency of immunization systems in developing countries. Given that immunization coverage is not yet absolute despite the existence of enabling technologies for several decades, the exploration of other influencers is warranted. An effective approach towards this endeavor is to study the decision-making process pertaining to routine immunization in developing countries.

Vaccines are a unique drug category in the sense that these are preventive agents

¹¹<http://www.villagereach.org/impact/openlmis/>

¹²<https://www.commcarehq.org/home/>

that are supposed to be administered to every child. Routine immunization, by virtue of being a large-scale public health exercise, is typically undertaken by governments. The governments are assisted by international agencies such as GAVI, Gates Foundation, UNICEF, WHO, and PAHO through, among others, technical and financial support as needed. By virtue of operating as a centralized ecosystem, immunization is particularly amenable to policy influence. The assertion of such influence for the incorporation of technology such as AIDC for tracking and tracing vaccines, however, is riddled with challenges.

A key challenge to drive and harmonize policy towards incorporation of AIDC is reconciliation of ground realities to intended outcomes of technological interventions. For instance, VPPAG recommends incorporation of barcodes at all packaging levels except the primary level ¹³. These recommendations are aligned with directives from several governments for incorporation of barcodes as previously noted. Several pharmaceutical firms have, however, contested the directive on the grounds that these render the vaccines prohibitively expensive to distribute and most developing countries do not have the infrastructure to leverage the barcodes in the first place. As a result, the enforcement of such directives has met with skepticism from the manufacturers ¹⁴.

The second challenge is ensuring basic harmonization at the policy level across countries towards the implementation of AIDC technologies. At present, no global consensus exists on the use of open standards for barcodes. In addition, the requirements pertaining to information encoded in barcodes vary across countries as well as consumers and customers ¹⁵. China, for instance, requires inclusion of barcodes compliant with its national standard on imported drugs in addition to any that might already exist ¹⁶. India, on the other hand, has demonstrated laxity in enforcing time

¹³http://www.who.int/immunization/policy/committees/VPPAG_Generic_PPP_and_Workplan.pdf

¹⁴http://www.ipapharma.org/news/Drug%20Information%20Centre%20Bulletin%20Volume%205/Drug_Information_Bulletin__37__05.pdf

¹⁵Joseph Mbirizi, UNICEF Supply Division Denmark, personal communication, April 1, 2016

¹⁶<http://www.law360.com/articles/417178/pharma-cos-scan-your-drugs-for-proper-barcodes>

frames for incorporation of barcodes on exported drug packages ^{17,18}. The lack of consensus on policy standards drives the packaging costs higher for manufacturers as well as raises challenges to compliance with regulatory directives.

Demonstration of the value of standards-based AIDC technologies in a cost-effective manner is thus needed to not only inform policy formulation and harmonization but also catalyze its implementation. VacSeen is motivated by the need to demonstrate the value generated by AIDC technologies in order to propel their large scale adoption. Furthermore, I endeavor to demonstrate the value of AIDC technologies at the last mile in and of themselves in order to advocate their inclusion in primary packaging in addition to the other levels.

1.5.3 Systems Approach

The realization that a systems approach is well-suited to address challenges associated with vaccines is almost a decade old [1]. While the immunization ecosystem is of relatively centralized nature compared to other therapeutic agents, the implementation of policy is challenged by the diversity of ground realities across regions. In such a scenario, the key stakeholders have realized the importance of "networks of highly collaborative interactions" for the manifestation of solutions [1].

Our objective underlying the development of VacSeen is deployment on the field. As a result, I have attempted to not only structure the platform for ease of deployment but also studied key levers that can enable circumvention of some of the challenges that technology-anchored solutions typically face in this domain. Primarily, we have emphasized present and future collaboration with influential stakeholders from a technology and policy standpoint. It is often the case that such policy oriented decisions are taken based on experiential or tribal knowledge. We, however, intended to formalize the process of identifying key stakeholders and influencing policy. The application of systems approach in designing the implementation roadmap of VacSeen

¹⁷<https://www.securindustry.com/pharmaceuticals/india-gives-small-pharma-exporters-extends40/a2644/>

¹⁸<http://www.in-pharmatechnologist.com/Regulatory-Safety/India-Pushes-Back-Deadline-for-Barcodes-on-Primary-Drug-Packages-Again>

is anchored to this intention.

1.6 Thesis Questions

One of the most satisfying aspects of the project for me has been the opportunity to flesh out the project objective and scope. In doing so, I identified a set of interrelated questions that I attempted to answer through my investigation. The questions along with attendant contextual information are listed below:

- It became evident early on during my research that an effective solution for improving vaccine access will necessitate incorporation of concepts and ideas from multiple disciplines. Had the issues been unidimensional, one that could be resolved solely through technological intervention or policy implementation, it would most likely have been dealt with by now given the tremendous progress in these domains in the recent past. Since that clearly is not the case as laid out by the evidence I present, the thematic question that the thesis seeks to address is *what ought to be the role of technology and policy in enabling equitable vaccine access for every child in the developing world*. The role of technology is viewed through the prism of VacSeen as well as its enablers, particularly AIDC, Semantic Web, and Linked Data technologies and standards.
- While it is intuitive to posit the application of technology and policy in fostering vaccine access, one ought to also consider the fact that immunization ecosystem is essentially a complex socio-technical ecosystem. Any intervention that does not address this complexity is prone to failure. In such a scenario, formally characterizing the system becomes a critical success factor. An applied question I investigate is *whether a systems approach is an effective method to relationally map technology and policy in order to prepare an objectively compelling case for implementation of the solution*.
- The second applied question for the thesis is *what factors need to be taken into consideration to determine the value of capturing vaccine administration data*

at the last mile so that the benefits from approaches such as incorporation of AIDC technologies can be assessed in detail. While presenting my proposal of fostering interoperability of data from last mile logistics to the stakeholders of the immunization space, a question whose variants I often found myself answering was 'What is the problem you are trying to solve?'. Each stakeholder has its own interpretation of what the utility and objective of data emanating from vaccine logistics is. While not unexpected, the question, to me, is symbolic of the dissonance that exists between their interests even when their overarching goal is the same, that of ensuring complete immunization of every child born in the world.

1.7 Contribution

The interventions aimed at improving vaccine access can be broadly classified into four axes as depicted in figure 1-3.

1. *Product Development*

From a product development standpoint, two overarching approaches characterize ongoing efforts to develop essential vaccines: reduction in the frequency of consumption through combination of vaccines and enhancement in the robustness of vaccines to reduce their vulnerability to temperature-induced damage.

2. *Supply*

Enhancement of immunization supply chains represents a key focus of the global health community in the context of vaccine access. Efforts by policy-oriented groups such as VPPAG to establish and harmonize packaging standards are complemented by those by myriad service providers to improve cold chain performance.

3. *Information Technology*

While Information Technology essentially impacts all aspects of a vaccine's life

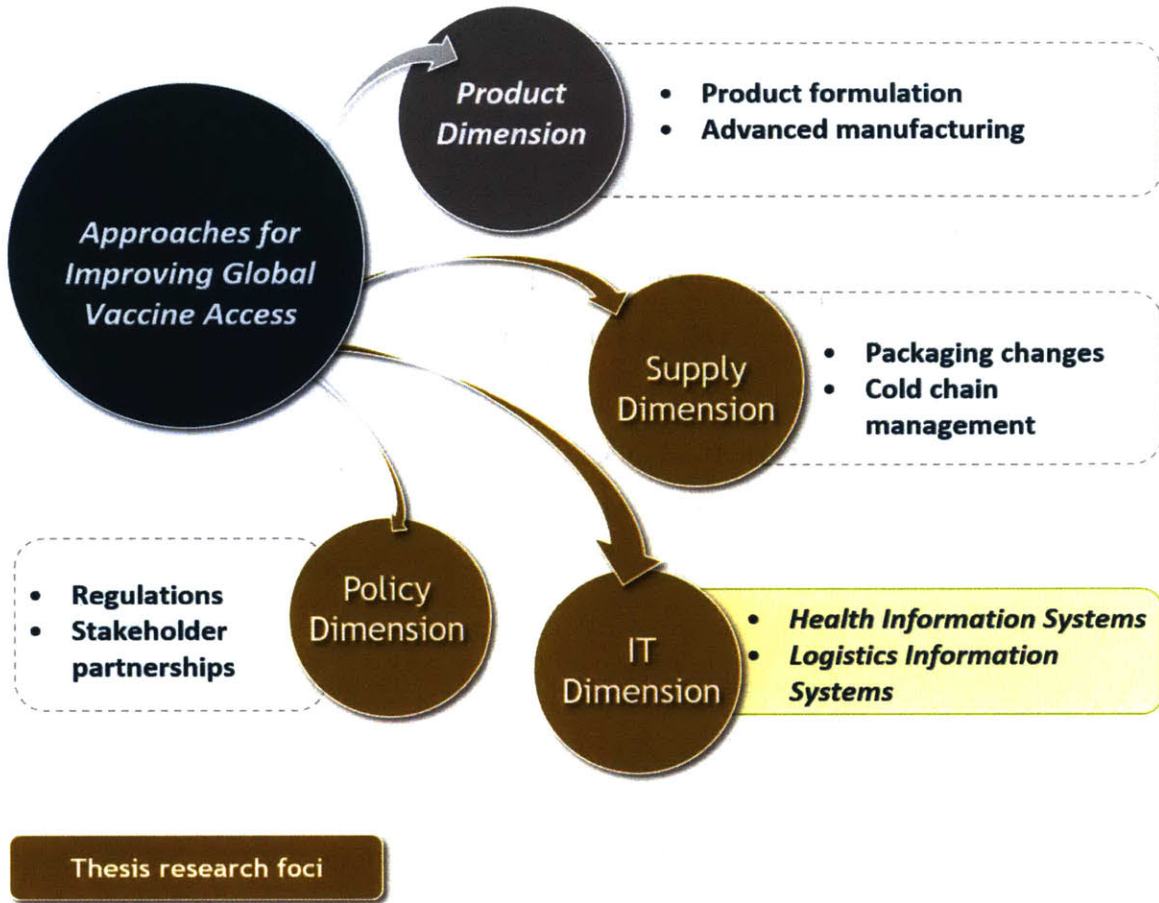


Figure 1-3: Classification of Interventions for Improving Vaccine Access

cycle, an area of particular focus in the context of developing countries is designing and linking health and logistical information systems. Such initiative is critical to enable the transition from paper-based record collection systems that have largely remained as the primary data capture mechanism since the 1970s when WHO established Expanded Programs for Immunization (EPI) across countries [36].

4. Policy

Immunization rates in large parts of the developing world have stagnated at around 80% implying that one out of every five children does not have access to essential vaccines [36]. There is thus an increasing realization that innovative approaches are necessary to ensure vaccine access for the "fifth child". As a result, policy directives have, of late, focused on generating more actionable

insights such as root causes underlying subdued vaccine access instead of mere indication of uneven coverage based on geography, improving data quality, and timeliness of data reporting. Such goals are articulated in the objectives of the presently ongoing 'Decade of Vaccines' initiatives [36].

Of the four axes, VacSeen's focus excludes the dimension of product development. From the perspective of cold chain management, I report our development of a low-cost sensor for detecting temperature excursion beyond permissible limits for vaccines, that are typically thermolabile, during transportation and storage. This hardware development is complemented with a software platform for tracking and analyzing last mile consumption data of vaccines using barcode scans. Through the software platform, I demonstrate the utility of Semantic Web technologies in fostering interoperability of data between information systems pertaining to vaccine access. A critical bottleneck that technological solutions face during implementation is their inability to fit into the policy roadmap that plays a critical role in shaping the contours of immunization programs. We address this challenge by characterizing the ecosystem of immunization using a systems approach and identifying the key policy levers that need to be actuated in order to attain successful deployment of the platform.

Chapter 2

Background and Literature

The body of literature encompassing the application of barcodes to immunization, temperature sensing for vaccines, and applications of Linked Data technologies is deep and diverse. The literature that treats the confluence of the three domains is limited. I report literature pertaining to each of these domains separately and subsequently demonstrate the utility of their co-application.

2.1 Related Work

2.1.1 Barcodes in Vaccine Logistics

Several studies have reported the effectiveness of using barcodes in tracking vaccine consumption. Au *et al.* report a case in which replacing pre-existing digital data entry with barcode scanning enabled reduction in time required for documentation as well as improved the accuracy of vaccine lot number entry from 95.4% to 100% [4]. Laroche *et al.* report a pilot study in Canada where replacing manual entry with barcodes resulted in 33% reduction in immunization errors as well as 48% to 69% reduction in time to record data [28]. A larger Canadian study by Pereira *et al.* reported significant lowering of immunization recording errors using barcodes but not difference in the time needed for data entry [38]. The results were an improvement compared to a similar study by the authors earlier who reported that while error count

was low, barcode scans in general were considered time consuming in high product volume clinics. The nurses administering the vaccines particularly noted issues with scanning two-dimensional (2D) barcodes [37].

The Center for Disease Control and Prevention (CDC) has reported that 2D barcodes will become the industry standard for secondary barcode packaging by 2017. This assertion is based on the the need for vaccine manufacturers to comply with Drug Supply Chain Security Act (DSCSA) that mandates the application of serialization on saleable units before November 2017 [27]. The incorporation of 2D barcodes was considered necessary because the linear barcodes on vaccine packaging—mandated for adoption in 2004—only encoded the National Drug Code (NDC) and not the vaccine lot number and expiry date data [20]. The CDC, based on its pilot study, has concluded that while 2D barcodes will enable improved inventory management thus benefiting downstream members of the supply chain, the limited financial abilities of smaller vaccine manufacturers and lack of coordination within the industry pose challenges to full utilization of the technology [27]. It is apparent that developed countries have graduated to discussing the 'how' of barcode incorporation from 'why'. One can also argue that the case is not particularly different in the context of developing countries.

The VPPAG concluded came to the following conclusions in 2013:

- *"There are no longer any major obstacles to the introduction of barcodes on secondary packaging and packaging containing secondary packaging."*, and
- *"Adding barcodes with lot number and expiry date information to primary packaging (the vaccine vial or ampoule) poses a technical challenge that may take several years to overcome."* [45]

The policy directive complements an increasingly voluminous body of work in resource-constrained settings for adoption of AIDC technologies in the context of immunization. Katib *et al.* report the development of a smartphone application for tracking vaccine coverage in rural communities by integrating data from multiple sources using, among others, QR codes [25]. Studies have been undertaken in Africa

where barcode scans have been utilized by nurses to present information pertaining to therapy received by patients [15]. Such academic and public sector intervention is being complemented by those from non-profit organization as well as social enterprises. Organizations mentioned in section 1.5 such as PATH, Dimagi, VillageReach, Logistimo, and VaxTrac are increasingly engaged in leveraging AIDC technologies for improving immunization access in developing countries.

While the utility of barcodes in improving vaccine logistics is not under dispute, a key barrier to adoption is the absence of objective evidence of benefits from such an endeavor in resource constrained settings. I did not find publications that quantify the benefit of adoption of barcodes in developing countries in terms of supply chain performance and/or compliance rate of recipients. The generation of such data is critical to inspire widespread adoption of the technology. The quantification of the benefits is a key objective of PATH in the Tanzania barcode project described in section 1.4. VacSeen has been developed with the goal of enabling quantification of such benefits.

2.1.2 Temperature Sensing of Vaccines

Two fundamental approaches underlie the efforts to maintain product integrity as a function of temperature. The first is development of thermostable vaccines that offset or minimize the need for cold chain transportation and storage. While such vaccines are expected to improve coverage, minimize wastage, and reduce costs substantially, multiple challenges pertaining to product formulation limit their adoption ¹. The second approach is establishing cold chain integrity of the vaccine supply chain to ensure that vaccines are transported and stored under optimal temperature conditions. The relatively better technical and operational feasibility, cross-product applicability, scalability, and immediacy have fostered extensive adoption of the second approach. To monitor the effectiveness of the cold chain, the product temperature needs to be reliably measured throughout the supply chain to detect temperature excursions be-

¹http://www.pharmaceuticalcommerce.com/index.php?pg=supply_chain_logistics&articleid=27206&keyword=biopharma-cold%20chain-logistics-forecast

yond both low and high thresholds. However, the research on vaccine cold chain has traditionally been skewed towards protecting the products from heat exposure. It is over the last decade that freezing has been recognized as a bigger problem than heating [24]. A widely cited study by Matthias *et al.* reports that 75%-100% of vaccine shipments are accidentally exposed to freezing temperatures at some point in the distribution chain, and 14%-35% of refrigerators or transport shipments expose vaccines to freezing temperatures [32]. The fact that temperature monitoring becomes increasingly challenging and inefficient as the products move deeper into the supply chain compounds the problem.

At the last mile Vaccine Vial Monitors (VVMs), thermochromatic labels affixed to vials, are the most extensively used tools for detecting temperature breaches. While freeze detecting monitors also exist, VVMs are most widely used to detect heating of vaccines. The 'shake test', a visual inspection-based approach that relies on differences in aluminum adjuvant settlement, is the most commonly used method to detect freezing. The test has been reported to be the only test with error-free sensitivity, specificity, and positive predictive value to determine whether aluminum-adjuvanted freeze-sensitive vaccines have been affected by freezing [24]. Other freeze indicators in application include cold-chain monitor indicator strips and liquid-based products^{2,3}. Despite the availability of options, vaccine freeze detection at the last mile of the supply chain remains suboptimal. Most freeze indicators used in the last mile rely on visual inspection. Such manual methods are cumbersome in typically manpower-constrained settings and susceptible to human error. More importantly, such methods do not lend themselves well to electronic information capture.

Low-cost RFID-based sensors present an attractive alternative for temperature sensing of vaccines till the last mile. By providing an inexpensive, easy-to-use, and automated information capture mechanism, such sensors mitigate some of the core challenges associated with end-to-end monitoring of vaccines. Such an application

²http://www.unicef.org/supply/files/Temperature_Monitoring_Devices_Vaccine_Storage_and_Distribution.pdf

³http://solutions.3m.com/wps/portal/3M/en_US/Microbiology/FoodSafety/product-information/product-catalog/?PC_Z7_RJH9U523003DC023S7P9203087000000_nid=71PHMRZCJCbeX2JZNTZSLTg1

will draw from a wide variety of work in using RFID-based sensing for a variety of applications. Bhattacharyya *et al.* have demonstrated the application of low-cost RFID tag antenna-based sensing for diverse applications such as surface crack detection and liquid level detection [9, 10, 23]. An example of crack detection using low-cost passive RFID chips on top of them has been demonstrated by Caizzone *et al.* [14].

RFID-based temperature sensing of perishable goods has been an active research area over the last decade. Bhattacharyya *et al.* have demonstrated the utility of tags as cheap and reliable temperature threshold sensors [9]. Others have demonstrated that application of RFID in monitoring agricultural products successfully in the supply chain. For instance, Qian *et al.* used a combination of 2D barcode and RFID to track wheat [39]. Ziai *et al.* reported the development of a temperature sensor for cold chains through changes in passive RFID tag response based on position of a moving metallic plate [49]. On the commercial front, several products exist in the market to enable temperature monitoring of perishable items such as vaccines ^{4,5,6,7}. However, key factors such as hardware and software weaknesses, relatively high cost of supporting infrastructure, and lack of scientific literature on effect of RFID exposure on tagged products limit the adoption of RFID technology in the pharmaceutical sector in general [29]. Additionally, the inflexibility of sensing mechanism renders RFID-based sensors inappropriate for deployment in resource-constrained settings where vaccine damage is most likely. The inability of a sensing mechanism to be deployable throughout the chain compromises end-to-end product quality assurance.

2.1.3 Application of Linked Data

Following the seminal publication that introduced Linked Data in 2001 by Lee *et al.*, several research arenas have spawned in the domain [7, 11]. A large section of Linked Data and Semantic Web research has focused on discovery and linkage of data on the

⁴<http://www.avantetech.com/products/supply-chain/cold-chain/>

⁵<http://www.caenrfid.com/en/Product.jsp?parent=65>

⁶<http://www.in-pharmatechnologist.com/Processing/Temperature-sensing-RFID-chip-could-cut-shipment>

⁷<http://www.alvinsystems.com/resources/pdf/MobileRFIDSensor.pdf>

web with the intent of making the world wide web more 'intelligent'. In essence, the objective of semantically enriching data is to enable the transition of the web from a network of interlinked pages to a network of interlinked data. Several developments bear testimony to this evolution of the web.

At the foundation is the establishment of the semantic web technology stack as depicted in figure 2-2a [21]. Much of the academic activity pertaining to semantic web

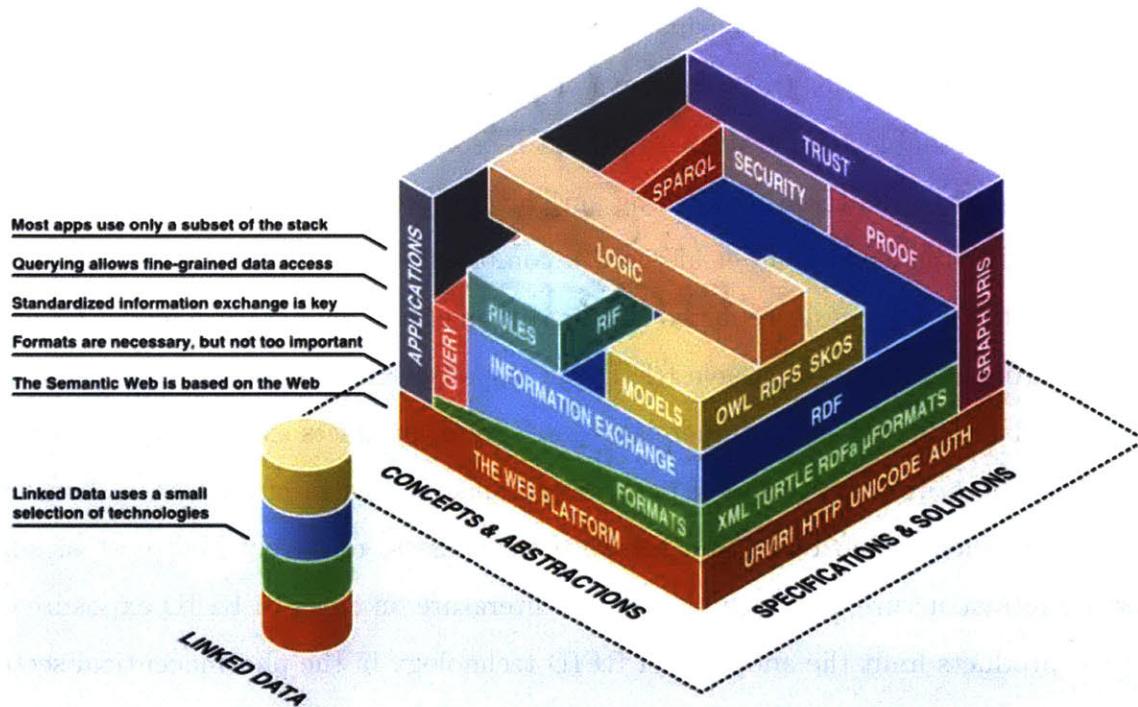


Figure 2-1: Semantic Web Technology Stack

(a) Source: Reproduced with permission from OpenHPI

initially centered around development of standards such as those pertaining to data modeling, querying, and transformation approaches; development of stable tools; and fostering adoption of Linked Data standards. In the context of the latter, establishment and dissemination approaches such as "Five Star Data" has been a focus area⁸. With the maturation of underlying technology and standards, greater emphasis now lies on implementation of data modeling and inferencing approaches.

The development of technical standards has been complemented by generation of Linked Data with the overarching goal being creation of the Semantic Web. Some of

⁸<http://5stardata.info/en/>

the key drivers of extensive Linked Data on the web are Open Government Data, social data, and partial mapping of open source knowledge repositories such as *wikipedia* to structured formats such as *dbpedia*. The burgeoning linkage between data is represented using the Linked Open Data (LOD) cloud⁹. In addition to the *de novo* generation of Linked Data, there has been a push towards semantically enriching existing data on the web using microformats in a bid to enable 'semantic search'. The extensive leverage of Knowledge Graph, a knowledge base drawing extensively from the LOD cloud, is an indicator of the progress in this direction¹⁰. The manifestation of the latter endeavor is *www.schema.org*, an initiative by leading search engines—Bing, Google, and Yahoo!—to establish a standardized set of schemas for structured data markup [42].

The third focus of Linked Data research has been knowledge representation and management. Ontology engineering and ontology-based application development have thus grown at a rapid pace. In addition to widely used general-purpose vocabularies such as *dbpedia*, *foaf*, and *skos*, a multitude of domain-specific ontologies exist^{11,12,13}. Ontologies have witnessed particularly high adoption in the life sciences and healthcare domain. As per the 'State of LOD Cloud' in 2014, life sciences had one of the highest usage of proprietary as well as open vocabularies and datasets¹⁴. This development is in contrast to the sector's reputation as one of slower adopters of ICT. Parsia *et al.* report that BioPortal, a comprehensive repository of biomedical ontologies, has some of the highest proportions of ontologies by sizes based on the number of axioms as depicted in figure 2-4a [31].

The ontologies developed pertaining to vaccines have primarily had a biomedical focus with applications in mining clinical data. Vaccine Ontology has been developed as a representation of vaccines in terms of their components, phenotypes, and host

⁹<http://lod-cloud.net/>

¹⁰<https://googleblog.blogspot.co.uk/2012/05/introducing-knowledge-graph-things-not.html>

¹¹<http://dbpedia.org/>

¹²<https://www.mpi-inf.mpg.de/departments/databases-and-information-systems/research/yago-naga/yago/>

¹³<https://www.w3.org/2004/02/skos/>

¹⁴<http://linkeddatacatalog.dws.informatik.uni-mannheim.de/state/>

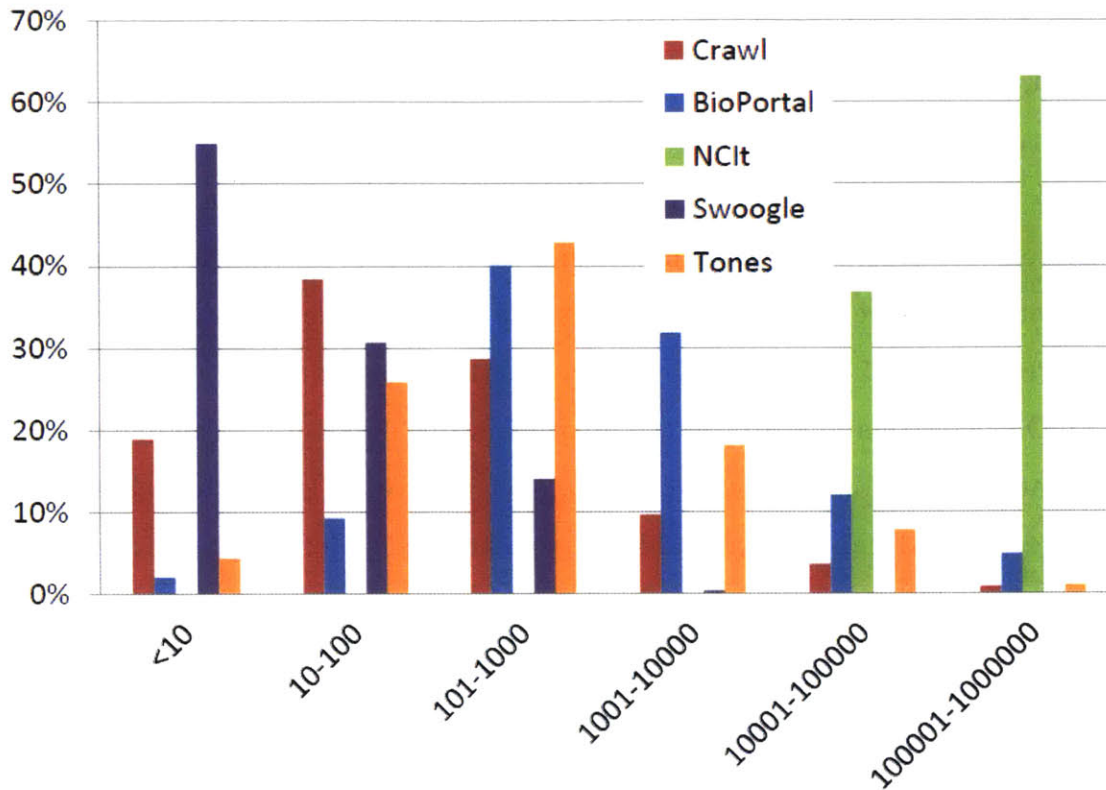


Figure 2-3: Proportions of Ontologies in Size Bins Based on Number of Axioms
 (a) Source: Parsia *et al.*

immune responses [22]. The ontology has subsequently been combined with the Ontology of Adverse Events (OAE) to develop the Ontology of Vaccine Adverse Events (OVAE) and mine vaccine adverse event data [30]. In addition to these specialized ontologies, vaccines have been included in general purpose ontologies such as *dbpedia*, *yago*, and *skos*.

The application of Linked Data in the realm of logistics has been demonstrated. Solanki and Brewster demonstrate the concept of 'linked pedigree' in pharmaceutical supply chains using Linked Data as a traceability and anti-counterfeiting measure [44]. Robak *et al.* exemplify the application of Linked Data in Business Process Management in supply chains [41]. In addition, efforts are underway to extend the GeoKnow platform for connecting Spatial Linked Data to enterprise supply chain data¹⁵. However, we were the first to demonstrate the application of Linked Data

¹⁵<http://geoknow.eu/wp5.html>

to improving last mile vaccine logistics through barcode scan validation and linking supply chain data to the LOD cloud [8].

The application of Linked Data is not limited to the realm of academic research. Sectorial applications using the technology range from retail and energy to music and newspapers^{16,17}. In fact, the technology has emerged as a core focus of firms such as Cambridge Semantics, MarkLogic, and Ontotext and is being applied for Enterprise Data Management^{18,19,20}.

However, much needs to be accomplished before Linked Data experiences the scale of uptake that legacy technologies such as XML have done so far. The pioneers of Linked Data technology concede that the contours and extent of the technology evolution have surpassed their expectations. For instance, the Web Ontology Language (OWL) has been fairly successful as a knowledge representation tool. However, its utility in porting the representation to the web has been suboptimal. Issues such as misuse of properties like *owl:sameAs*, inconsistency in usage of Class definitions from OWL and Resource Description Framework Schema (RDFS), and poor linkage between ontologies are representative of the phenomenon¹⁶. Efficient approaches to ontology discovery and incorporation are yet to be developed. Lastly, the extent of preparation and knowledge necessitated by the technology tends to be prohibitive for consumers. Given that the success of the web of data ultimately hinges on the ability of its consumers to produce as well as consume Linked Data, such challenges need to be addressed in order to ensure deployment of the technology at scale.

¹⁶<https://www.youtube.com/watch?v=oKiXp02rbJM>

¹⁷<http://www.cambridgesemantics.com/semantic-university/example-semantic-web-applications>

¹⁸<http://www.cambridgesemantics.com/>

¹⁹<http://www.marklogic.com/what-is-marklogic/features/semantics/>

²⁰<http://ontotext.com/>

Chapter 3

Platform Design and Development

3.1 Software

3.1.1 Barcode Scan Validation

The presence of barcodes on packaging presents the opportunity for using an EPCIS v1.1¹(Electronic Product Code Information Services) event as a proxy for a vaccine transaction event. EPCIS is a standardized event oriented specifications prescribed by GS1, a standards organization,² for enabling traceability. Here a transaction event can either be traversal through the supply chain or the administration of the vaccine. By including barcode scanning as a required step in standard operating procedure, a record of every vaccine receipt event can be stored.

VacSeen set-up for scan validation, developed entirely using open source tools, comprises an Android application for barcode scanning, a server that hosts multiple relational databases, an ontology for mapping the conversion of relational data into Linked Data, a triple store for storing the converted Linked Data, and a web-based visualization platform (Fig 3-1).

¹<http://www.gs1.org/gsm/kc/epcglobal/epcis>

²<http://www.gs1.org/>

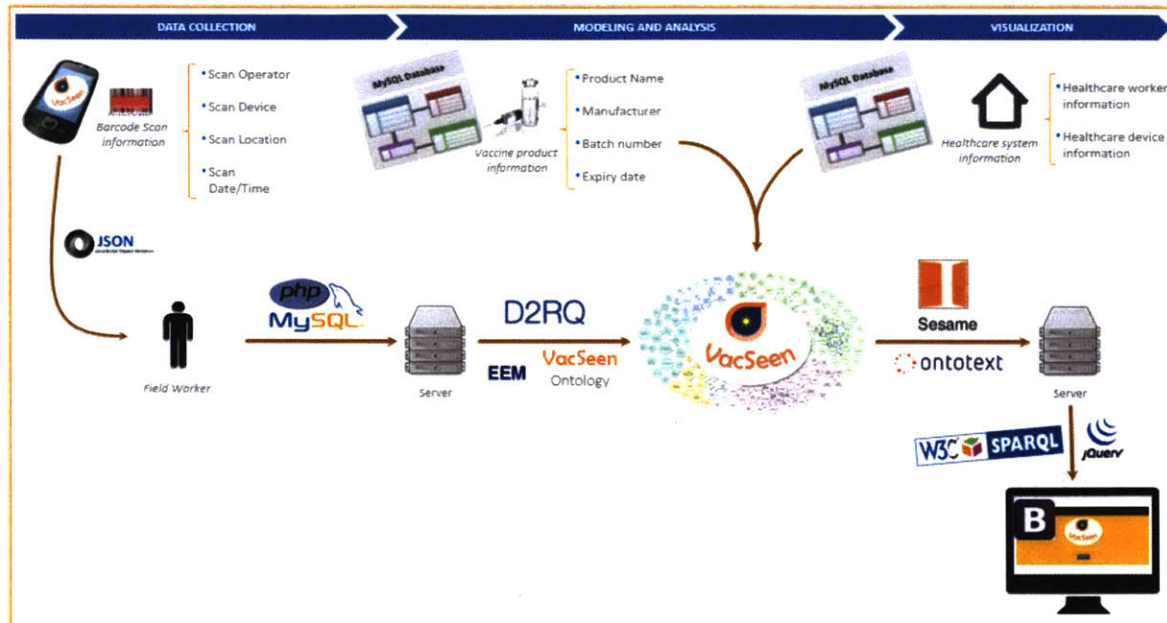


Figure 3-1: Barcode Scan Validation - System Workflow

VacSeen Mobile Application

My focus while developing the Android application was testing a Minimum Viable Product in the field that I can add features to at subsequent stages of development. As a result, the role of the VacSeen application was confined to that of a generator for scan data.

The worker is expected to scan the barcode on vaccine's package as an identifier of a transaction event. I integrated the widely used Zxing barcode library³ into the application to facilitate barcode scanning. The app collects the following information that serve as components of the business rules for scan authentication:

- Content and format of the barcode scanned.
- Worker's phone number that serves as operator ID.
- The device's International Mobile Equipment Identity (IMEI) number that serves as device ID.
- Spatial and temporal data.

³<https://github.com/zxing/zxing>

Despite the availability of several other device identifiers, I chose the IMEI number because of its relative ubiquity and uniformity. The capture of IMEI number can give rise to concern among users as the application requests access to call records during installation. However, I assume that the users of the application are authorized personnel using government- or employer- issued devices as is often the case with immunization projects. As a result, I circumvent concerns about privacy breach that would otherwise typically arise.

Data storage

For storing and hosting the data, I used WAMP Server (Apache, PHP, MySQL on Windows)⁴. The data from VacSeen mobile application was stored in a MySQL database hosted on an Apache server with PHP as the server side scripting language. A JSON parser in the mobile application was used for transmitting the data which was then written into the database by a PHP script. I chose WAMP Server to mimic the use of MySQL on Windows computers in the barcode project in Tanzania.

In addition to the database for storing inputs from the mobile application, I created another database of authorized operators (scanning personnel) and devices (mobile phones) to mimic those likely to be used by the healthcare authorities. A representative database with product details from the barcode project in Tanzania was shared by PATH.

RDB-to-RDF translation

With numerous options available for Relational Database (RDB)-to-Resource Description Framework (RDF) translation [35], I employed the D2RQ Platform⁵ for my project, despite R2RML being the W3C recommended standard, for two reasons. First, D2RQ bears deeper logical similarity to RDF compared to R2RML which is closer to relational databases. Unlike D2RQ, the complexity of mapping using R2RML is largely centered on querying the relational database using *rr:sqlQuery*.

⁴<http://www.wampserver.com/en/>

⁵<http://d2rq.org/>

The second reason is the ability of D2RQ to support R2RML, particularly when dumping relational databases as RDF. Using D2RQ enables me to not only leverage an extensively used publicly available stable tool but also be compliant with standards in the future.

I used the D2RQ mapping tool and the dump generator for the project. To customize the mapping produced by the *generate-mapping* script, I used resources from multiple well-known vocabularies such as *dbpedia-owl*, *foaf*, and *eem* in addition to a self-created one named *VacSeen1*⁶. The mapping files are publicly available⁷.

I enforced integrity constraints on the data during translation by specifying datatypes in the mapping files. Additionally, I applied filters in the SPARQL queries to disregard records with incorrectly captured data fields.

Conceptualizing Domain Knowledge as Ontologies

For creating the *VacSeen1* ontology, I reused sections of the EPCIS Event Model ontology (EEM)⁸ and the Vaccine Ontology (VO)⁹. The incorporation of concepts from the two ontologies enabled me to seamlessly bridge logistical and biological information for my future applications. I generated persistent uniform resource identifiers (URIs) for the ontology elements and are currently working on making them dereferenceable. I used a light-weight ontology with just enough formalization to enable detailed querying. As the datasets attain greater complexity, it will be necessary to incorporate a higher degree of semantics within the ontology. However, I will position most of the complexity in my queries instead of the ontology in order to control for reasoning errors.

Since EEM offers an extensive model for EPCIS events, mapping the elements of the relational databases to classes and properties of the ontology was my default approach. However, I created additional properties and classes as needed. For instance, the location coordinates from the *VacSeen* application are stored in the *scan_event*

⁶<https://w3id.org/vacseenont>

⁷http://web.mit.edu/parthasb/Public/Vacseen_Customized_Mapping.ttl

⁸<http://purl.org/eem/#>

⁹<http://www.violinet.org/vaccineontology/>

table of the *vacseen_connect* database as *scanLat* and *scanLong* columns. To map the latitude and longitude coordinates, I created the *vacseen1:latitudeOfBarcodeScanEvent* and *vacseen1:longitudeOfBarcodeScanEvent* properties in the VacSeen1 ontology. Other customized properties include *scanID* and *operatorID*.

The scanID is a 20-digit composite unique identifier of a scan event generated from scan attributes to facilitate an intuitive understanding about it. The information encoded in the ID can be useful in implementing access controls, protecting personnel privacy, limiting data exchange volumes, and partially offsetting the ambiguity arising from multiple scans of unserialized Global Trade Identification Numbers (GTIN).

Data Storage

I evaluated both in-memory and cloud-based options for the storage of data. The details of the implementation are discussed below.

In-Memory Storage I chose GraphDB-Lite¹⁰ semantic repository implemented on Sesame for my project as it offers (*owl*) based reasoning and is free, stable, scalable, and easy to use because of an intuitive administrative interface that comes with the distribution. I used Apache Tomcat 8.0 servlet container as per the recommended installation settings on a personal computer.

I loaded data from the 3 databases—vaccine data, healthcare system data, and barcode scan data—(Fig 3-1) into a single triple store. Additionally, I selectively incorporated relevant data for my analyses from the LOD cloud to circumvent the issue of sporadic unavailability of public SPARQL endpoints. By having the data in a single store, I excluded the need for more complex federated SPARQL queries that tend to be resource and time intensive. As the volume of data scales, the triple store data storage and access architecture will, of course, require re-design but I do not explore that in this thesis.

¹⁰<http://ontotext.com/products/ontotext-graphdb/graphdb-lite/>

Cloud-Based Storage I subsequently ported the data to the cloud to ensure its continued availability in the event of issues with the in-memory set-up. I chose Dydra¹¹ because of its ease of use. As Dydra offers OWL-based reasoning only at a cost, I generated the inferred statements in GraphDB prior to porting the data. In terms of performance, I did not experience any major variance with queries on the VacSeen webpage being executed within 2 seconds depending on web connectivity and device. As my goal is to develop and maintain the platform solely using freely available and open source tools, I am considering alternatives such as one using the OWL API¹² and reasoners for at-scale service delivery.

3.1.2 Ontology Based Classification

With the development of the underlying system for data integration in place, I explored opportunities to evaluate VacSeen’s performance on large-scale real-world data. VaxTrac, a U.S.-based non-profit organization, appeared to be an attractive partner for such a project. VaxTrac tracks immunization by scanning barcodes on vaccine recipients’ health cards using mobile devices. The scanned data includes location and time stamps, type of vaccine, and identifiers of recipients. Given the similarity between the nature of data gathered by VaxTrac and those generated previously in developing VacSeen, I partnered with the organization to study the effectiveness of the latter for analysis of data in real world settings.

VaxTrac currently operates in Benin and Nepal. Benin presents a compelling case for the deployment of innovative information systems such as VacSeen. The West African country has witnessed a dip in immunization coverage rate of Oral Polio Vaccine (OPV) between 2006 and 2012 and no improvement in that of Bacillus Calmette-Guérin (BCG) vaccine [19]. In addition, the percentage of children who did not receive any vaccine increased from 7% in 2006 to 10% in 2011-12 [19]. It has also been estimated that current vaccine availability rate in the country is 93% due to transportation bottlenecks, and it is likely to dip further with the introduction of

¹¹<http://dydra.com/>

¹²<http://owlapi.sourceforge.net/>

new vaccines if the supply chain is not redesigned [13].

To address these unmet needs, I extended VacSeen through the VacSeen Ontology for Immunization Compliance (VOIC)¹³ and a data connector. When used in conjunction, the two components enable identification of vaccine recipients with incomplete immunization as per Benin’s schedule, and linkage of the records to product details to inform the subsequent intervention. In addition to VOIC, I used VO and OVAE that are described in Section 2.1.3. The application of these ontologies by mapping them to VOIC in order to develop the VacSeen classifier and decision-enabling tool for on-field deployment represents a novel use case for them. There is a pressing need for such tools in developing countries in order to ensure timely intervention for universal vaccine access.

The flow of data enabling the classification is illustrated in Fig 3-2.

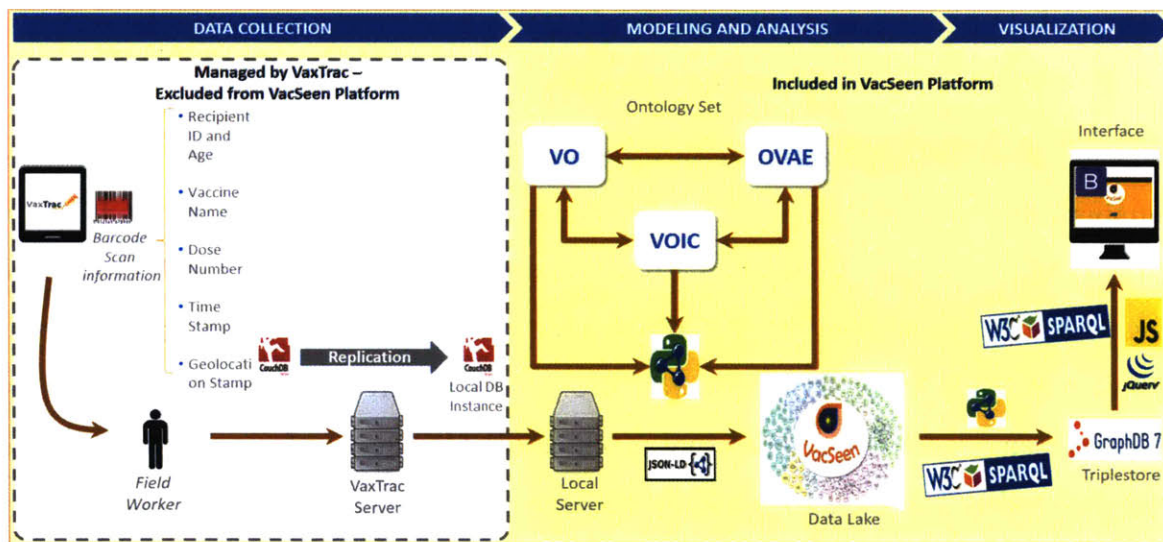


Figure 3-2: Flow of Data During Classification

The classifier application currently comprises RDFlizer scripts for non-RDF data in JSON format, the collection of VOIC, VO, and OVAE ontologies, GraphDB Free 7.0.0 as the triplestore, a web-based interface, and JavaScript connectors for query facilitation. These components with the exception of GraphDB are available on GitHub¹⁴.

¹³<https://w3id.org/voic>

¹⁴<https://github.com/parthasb/VOIC>

VaxTrac made the data it captured in the field available to me in the form of JSON documents through replication to a local CouchDB instance¹⁵. I filtered the data to remove test records and RDFlized the dataset using the json-ld module of RDFLib¹⁶, a Python library, and subsequently loaded the data into a triplestore using the SPARQL module. For storage and inferencing, I used GraphDB Free 7.0.0 with OWL-RL(Optimized) as the inference engine¹⁷.

A temporal bottleneck I overcame was with regards to using RDFLib for RDFlizing the records. Specifically, I encountered memory error when trying to parse about a gigabyte of sorted raw data using rdflib-jsonld. This experience is consistent with similar issues reported in user fora. I circumvented the error by altering the script to group the records by recipient identifier and funnel them through the module sequentially. This approach, however, is time-consuming with the program needing about 20 seconds to parse each recipient's records and add *isNotAdministered* relationships. I am exploring approaches to reduce the time required for executing the task.

I followed the RDFlization with insertion of 230,691 triples into the store. This number includes triples from RDFlized version of 5,100 records, and the VOIC, VO, and OVAE ontologies. A total of 1,094,985 triples were generated by the inference engine leading to storage of 1,325,676 triples in the store. The ratio between total number of triple to explicit ones was 5.75. I reconfigured GraphDB by allocating 8GB of memory for the Java virtual machine (JVM). Queries for count such as the one depicted in Listing 4.1 took approximately four seconds to execute.

The results from the queries are rendered on a web-based dashboard, a section of which is replicated in the VacSeen website. Given the sensitive nature of the records, I demonstrate the feature with anonymized data of 5 vaccine recipients. The query execution is done using ajax and is click-based. The queries typically take about 2 seconds to render output subject to device and quality of internet connectivity.

¹⁵<http://couchdb.apache.org/>

¹⁶<https://github.com/RDFLib/rdflib-jsonld>

¹⁷<http://graphdb.ontotext.com/>

Web Interface

The web interface of the project is publicly available¹⁸ and was built using the Bootstrap framework. [2] The interface presently enables querying a static dataset of EP-CIS events to display 3 levels of scan authentication using Google Maps, attendant analyses, Linked Data-based applications, as well as results from classification of records.

The marker data is generated by querying the Sesame triple store using the SPARQL query language over jQuery. In the absence of automated formatting of SPARQL queries in JavaScript, I formatted the queries through string concatenation. [33].

3.2 Hardware

3.2.1 Sensor Design and Fabrication

I began the process of developing a heat and freeze sensor for vaccines by focusing on the latter aspect first. As mentioned in Section 2.1.2, detection of freezing of vaccines at the last mile is a less studied problem than heating. The freeze sensor was designed, in collaboration with my peers, for simplicity of function and integration into normal vaccine carrying equipment, and consists of a small glass vial with an integrated RFID tag. The vial, as shown in, Fig 3-3 is filled with a fluid that expands during its phase change from liquid to solid.

Should the temperature of the container fall below a critical threshold for enough time, the fluid freezes, and the expansion causes the vial structure to deform and ultimately crack. This deformation is then harnessed to cause a detectable change in the RFID tag function, allowing the RFID reader to detect the change of state and possible spoilage of the vaccines in the associated container.

As a proof of concept, I used 2mL amber glass vials filled to the brim with commercially available distilled water and placed them in a freezer. The vials developed

¹⁸<https://w3id.org/vacseen>

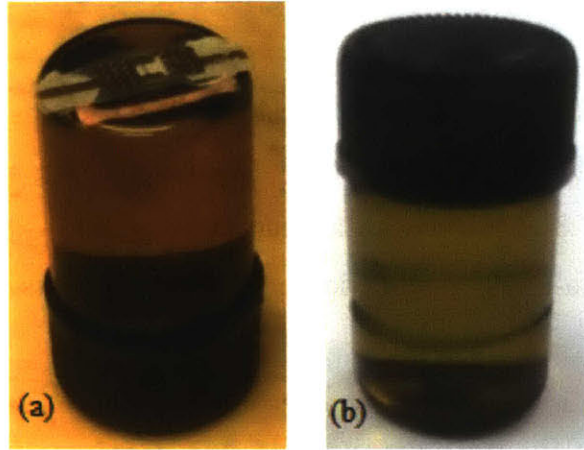


Figure 3-3: Top and Bottom View of Vial

fractures along their baseline as they froze. An RFID tag antenna was then designed by my collaborators for the vial with connections that extended over the region which developed the fractures. Simulations of the tag antenna design were performed using HFSS. In the configuration when the antenna was intact upon the surface of the water filled vial, the impedance match between the tag and antenna, often referred to as Tau, was found to be in the range of .02 to .04 as depicted in Fig 3-4.

While this low value translates into a very inefficient transfer of power from the antenna to the RFID chip and a low backscatter power level as shown by Dobkin, [16] the anticipated performance was adequate for the RFID tag to be readable at close range. In contrast, simulations of the same antenna with 1mm cracks in the two arms at the base of the vial returned a Tau ranging from .004-.005 Fig 3-4.

This makes it far more difficult for the tag ID to be read should the antenna develop significant cracks caused by vial deformation. The initial prototype antenna was constructed with copper tape that was placed on the vial in the position shown in Fig 3-5b.

An RFID chip harvested from an Alien Squiggle tag was then connected to the antenna with the help of conductive silver epoxy. The tag was readable from a distance of several centimeters using a small Nordic USB reader and an Impinj Speedway R420 RFID reader operating at 902 MHz-928 MHz. However, after the vial was placed within the freezer and the vial fractured, the tag remained readable as the copper

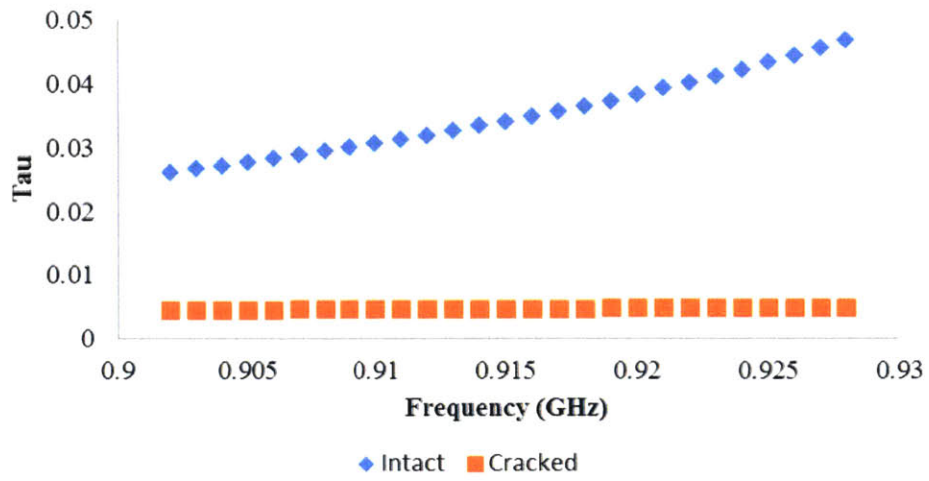
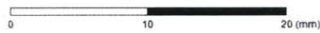


Figure 3-4: Comparison of Tau



(a) Simulated



(b) Fabricated

Figure 3-5: Conformal Mask

tape was robust enough to remain unphased by the vial cracking underneath. To address this issue, we shifted from an antenna made from copper tape to a deposited copper thin film. A thin film of copper would have sufficient electrical conductivity for the RFID tag to function, but would be embedded upon the glass vial surface. Lacking the structural rigidity of the copper tape, the antenna would not be susceptible to the fracture of the vial. To deposit the film, we utilized a conformal masking technique [18], [19] which enabled the deposition of the copper antenna pattern conformally to the glass vial despite the fact that the glass vial is far from the planar surfaces which are normally used for thin film deposition. A conformal mask, depicted in Figure 4, containing the antenna pattern was thus designed for the vials, and fabricated using an additive manufacturing process known as Fused Deposition Modeling.

Due to variability in the fabrication of the masks, some required a subsequent reaming step which enabled the vials to fit tightly within the mask. Mask and vial were then placed within a vacuum chamber, and argon sputtering was used to first deposit a 10nm adhesion layer of Titanium, followed by a 1 μm layer of copper.

With the copper pattern fully deposited on the vials as shown in Figure 5, RFID chips were again added using the conductive epoxy, and were found to be readable from a similar distance as before. After being placed in the freezer, however, the vials were found to be unreadable as the copper film cracks along with the underlying glass. It is this self-destruction of the tag that alerts the reader of a freezing event.

Chapter 4

Results and Discussion

4.1 Scan Validation

In this section I report information about vaccine scans, aggregate statistics, and description of two LOD-based applications as results from the barcode scan authentication study. For the purposes of this study, I make use of simulated data where 22 researchers and volunteers in United States and India were asked to scan barcode labels (vaccines or otherwise) randomly over a period of 28 days.

The users generated 217 scan events for analysis of which 20 events from 3 users did not capture the location coordinates of the scan and returned values of '0.0' for latitude and longitude. This is possibly a result of the lag experienced by devices at times to report their location coordinates. Subsequent versions of the mobile application will look to eliminate this problem by appropriate data buffering techniques.

4.1.1 Vaccine Scan Authentication

Several entities such as shipping agencies, inventory stock controllers, and healthcare workers, are engaged in vaccine logistics; all of whom can use VacSeen to scan barcodes during operations. It is therefore important to provide additional context for each barcode scan so as to get a deeper understanding about vaccine handling operations in the field.

EPCISEvent	GTIN	OperatorID	Latitude	Longitude
<http://purl.org/net/vacseeni/scan_event/12>	"123456788975"	2951	"42.3605085"	"-71.0949184"
<http://purl.org/net/vacseeni/scan_event/14>	"1234567890265"	3932	"42.3605299"	"-71.0948995"
<http://purl.org/net/vacseeni/scan_event/103>	"1234567890074"	3932	"42.3693664"	"-71.1890642"

(a) SPARQL Output - Intermediate Validation Query

EPCISEvent	GTIN	OperatorID	DeviceID	Latitude	Longitude
<http://purl.org/net/vacseeni/scan_event/14>	"1234567890265"	3932	28743	"42.3605299"	"-71.0948995"
<http://purl.org/net/vacseeni/scan_event/103>	"1234567890074"	3932	28743	"42.3693664"	"-71.1890642"

(b) SPARQL Output - Advanced Validation Query

collID	scanID	scanFormat	scanContent	deviceID	operatorID	scanLat	scanLong	scanDate	scanTime
10	05510720150413183323	UPC_A	718103141505	45507	2951	42.3605127	-71.0949068	2015-04-13	18:33:23
11	42510720150413183335	UPC_A	073852025842	45507	2951	42.3605065	-71.094907	2015-04-13	18:33:35
12	57510720150413183357	EAN_13	123456788975 *	45507	2951	42.3605085	-71.0949184	2015-04-13	18:33:57
13	57510720150413183451	CODE_128	MX0MW5584773979B0157	45507	2951	42.3605066	-71.0949253	2015-04-13	18:34:51
14	65324320150415181014	EAN_13	1234567890265 *	28743	3932	42.3605299	-71.0948995	2015-04-15	18:10:14
15	01510720150417071930	UPC_A	079400872401	45507	2951	42.3543835	-71.1033947	2015-04-17	07:19:30
16	21510720150417071953	UPC_A	011111014121	45507	2951	42.3543854	-71.1033898	2015-04-17	07:19:53
103	74324320150426021922	EAN_13	1234567890074 *	28743	3932	42.3693664	-71.1890642	2015-04-26	02:19:22
204	28324320150427021436	EAN_13	9780470526828	28743	3932	42.3605299	-71.1881035	2015-04-27	02:14:36
*Barcode GTINs	0150429113714	UPC_A	894700010106	28743	3932	42.3598301	-71.1890642	2015-04-29	11:37:14

(c) MySQL output - Eligible scans for Intermediate Validation

Figure 4-1: SPARQL and MySQL Output for Validation

To illustrate this, I randomly designated two authorized operators (IDs ending in '3932' and '2951') and an authorized device (ID ending in '1014' belonging to the first of the aforementioned operators). A scan by operator '3932' using device '1014', for example, can be used to indicate a vaccine administration scan by a healthcare worker while a scan by '2951' might indicate an inventory status scan by a non-healthcare worker.

Following are some authentication visibility statistics tested in the study:

- All Scans: Displays all of the 197 barcode scans (vaccine label or otherwise) by any operator and device using the VacSeen software.
- Basic Validation: Of the 197 scans, identifies the 37 scans that entailed scanning of a vaccine GTIN present in the supply chain database.
- Intermediate Validation: Distinguishes the 3 scans that were undertaken by the two authorized operators on vaccine GTINs (Fig 4-1a) as can be verified from the MySQL database (Fig 4-1b).

- **Advanced Validation:** Adds to the Intermediate Validation by distinguishing the 2 scans that were done using the sole authorized device. As the list of authorized devices only has one device registered to operator '3932', one of the scans registered in Intermediate Validation does not qualify as an Advanced Validation (Fig 4-1c).

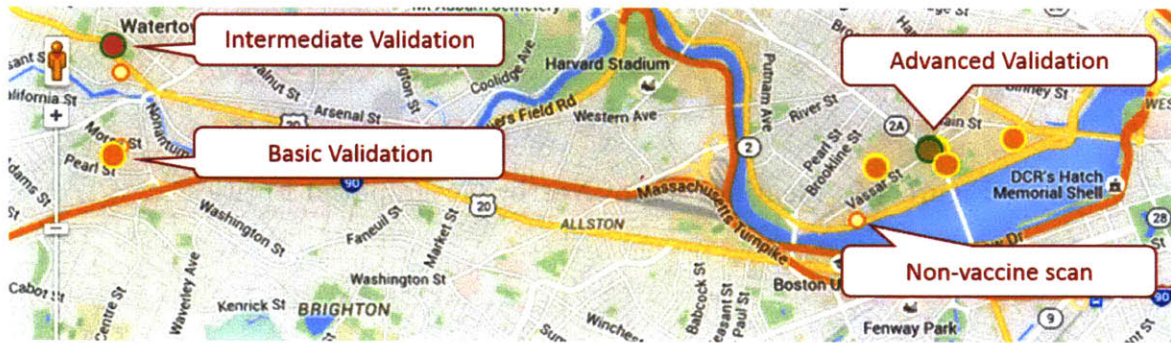


Figure 4-2: Visualization of Validated Scans

The differences among the validation levels are illustrated in Fig 4-2.

4.1.2 Operator and Device Scan Statistics

In addition to barcode scan validation, I undertook preliminary analyses of the data to assess operator performance by measuring scans by devices and visualizing overall temporal trends in scans. Visualization of aggregate statistics was useful in determining individual and collective user activity which can be considered representative of analysis of personnel efficiency during enterprise applications.

4.1.3 Linkage to LOD Cloud

To demonstrate the benefit of linkage to the LOD cloud, I generated biomedical factsheets about the vaccines comprising information such as type, route of administration, and Medline and Anatomical Therapeutic Chemical (ATC) numbers from DBpedia [5]. I use the *owl:sameAs* property to equate resources in the native dataset to those in DBpedia. I also developed an application to identify the nearest airport to a scan location to assist in endeavors such as logistical planning and product recall as

shown in Fig 4-3. For identifying the nearest airport, I used the *SPARQL SERVICE* feature and the *omgeo:nearby* property. This feature is a representative approach to geolocating other entities of interest corresponding to the scan sites.



Figure 4-3: Identification of Nearby Geographical Entities

For instance, mashing scan density data with location of healthcare centers, hospitals, and warehouses can help generate rich insights about product movement and consumption. Such applications demonstrate that Linked Data technology can leverage the burgeoning open and structured data on the web more easily and seamlessly relative to relational database systems.

4.2 Ontology-Based Classification

This section reports the results from VOIC-driven classification of data received from VaxTrac and its subsequent linkage to the LOD cloud. I used the ontology to classify records of 5,100 recipients from VaxTrac's database. The findings are summarized in Table 4.1 and the corresponding probabilities of correctly captured records are depicted in Fig 4-4. It must be noted that the total number of records is not a direct sum of the other classes as there are overlaps between them as per the axioms discussed in Section 3.1.2. In addition, the probability of correct records is lower than the actual probability of immunization because of the exclusion of vaccine recipients with errors in their records.

Table 4.1: Compliance of Recipients to Immunization Schedule

Vaccine	Dose					Erroneous Records
	1	2	3	4	Total	
BCG	1908	-	-	-	1908	0
DTwPHibHepB	2449	1596	0	-	3482	1102
IPV	30	-	-	-	30	0
Measles	1459	-	-	-	1459	0
OPV	1905	1183	781	491	4158	2331
Pneumo_conj	2451	1595	0	-	3484	1102
YF	1456	-	-	-	1456	0
TT	0	0	0	0	0	0

Total Number of Recipients = 5100

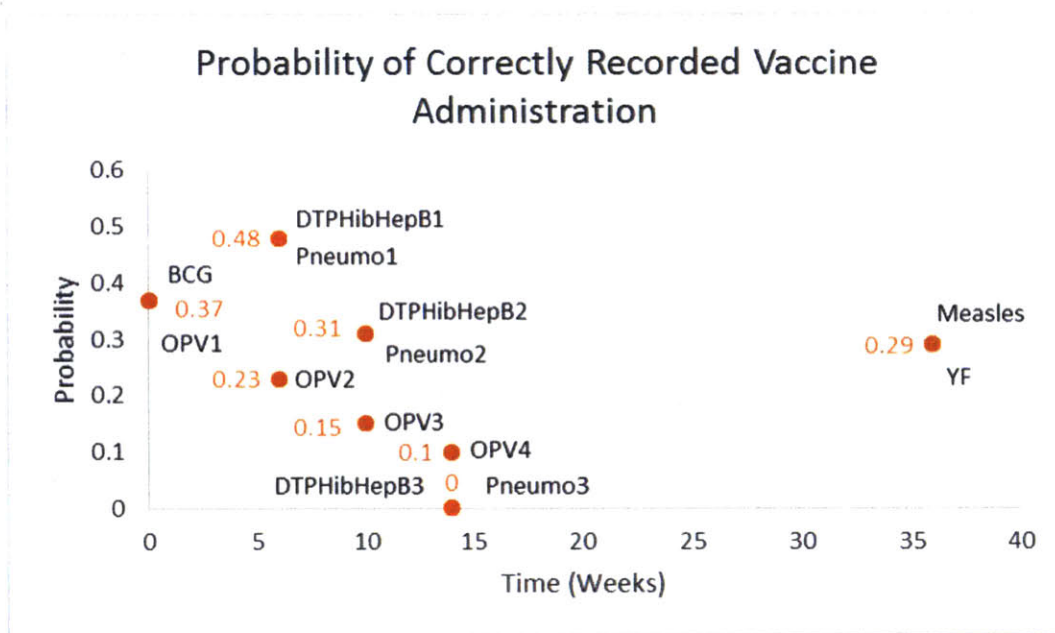


Figure 4-4: Probability of Correct Records Arranged by Recommended Immunization Schedule

It is evident from the data that while the fraction of correct records for the first dose is in the range of 30%-50%, the numbers drop progressively with subsequent doses in the case of multidose vaccines such as *Pneumo_conj* and *OPV*. This observation

is consistent with the literature where coverage rates in Benin have been shown to drop from over 80% for the first dose of OPV to 56.2% for the fourth dose [19]. Another interesting observation is the near identical probabilities of co-administered vaccines such as *YF* and *Measles*. Such close coupling indicates that that clustering of administration is potentially an effective approach to enhance compliance, and that it is likely that availability of different vaccines is reasonably well managed. It must, however, be pointed out that these observations do not take into account factors such as the actual age and identity of the recipients that could impact the result. I are currently in the process of undertaking more in-depth analysis of the data by including such factors.

One of the key design choices in developing the ontology is top-level simplicity and easy accessibility to data given the constraints of the environments where I expect it to be used. As a result, I contained the conceptual complexity in the axioms such that top level data can be readily accessed using intuitive single line queries. The simplicity is manifest in the portion of the query, depicted in Listing 4.1, used to generate the data for Table 4.1.

Following the classification, I used standard SPARQL queries as recommended by the authors of VO and OVAE to generate the list of brand names for vaccines as well as adverse events related to them. In particular, I used *obo:IAO_0000118* in addition to *rdfs:label* to ensure comprehensiveness of results as both the relationships are used in the ontologies for labeling resources.

I demonstrate the application by querying for pneumococcal vaccines and subsequently choosing *Prevnar* for display of a selection of known adverse events. The results of the query are depicted in Fig 4-5. I must point out that pneumococcal vaccines and *Prevnar* are used for illustration only and I make no implications about the extent of prevalence or severity of adverse events associated with it in Benin or elsewhere.

Listing 4.1: Query for Count of Recipients by Dose

```

PREFIX obo: <http://purl.obolibrary.org/obo/>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX : <https://w3id.org/voic#>

SELECT
(COUNT (DISTINCT ?dtpHiHepRecipient) as ?dtpHiHepTotalCount)
(COUNT (DISTINCT ?dtpHiHep1Recipient) as ?dtpHiHep1Count)
(COUNT (DISTINCT ?dtpHiHep2Recipient) as ?dtpHiHep2Count)
(COUNT (DISTINCT ?dtpHiHep3Recipient) as ?dtpHiHep3Count)

WHERE {
  {?dtpHiHepRecipient a :DTwPHibHepRecipient .}
  UNION
  {?dtpHiHep1Recipient a :DTwPHibHep1Recipient .}
  UNION
  {?dtpHiHep2Recipient a :DTwPHibHep2Recipient .}
  UNION
  {?dtpHiHep3Recipient a :DTwPHibHep3jRecipient .}
  UNION
  {?dtpHiHepError a :DTwPHibHepRecipientWithErrorRecord .}
}

```

1	Pneumovax 23 (USA)	1	Prevnar-associated injection-site erythema AE
2	Prevnar (USA)	2	Prevnar-associated injection-site induration AE
3	Prevnar 13	3	Prevnar-associated injection-site tenderness AE
4	Streptococcus pneumoniae vaccine	4	Prevnar 13-associated injection-site tenderness AE
5	polyvalent pneumococcal vaccine	5	Prevnar 13-associated injection-site redness AE
6	Synflorix	6	Prevnar 13-associated fever AE
7	Pneumo 23	7	Prevnar 13-associated injection-site pain AE
8	Pneumovax 23 (Canada)	8	Prevnar 13-associated joint pain AE
9	Prevnar (Canada)	9	Prevnar 13-associated chills AE
		10	Prevnar 13-associated rash AE

(a) Pneumococcal Vaccine Brands

(b) Prevnar - Selected Adverse Events

Figure 4-5: Brands and Adverse Event Information

4.3 Temperature Sensing

To demonstrate that the sensors work, I exposed them to the freezer of a household refrigerator. As part of the set-up, I placed the antenna of the Impinj Speedway R420

Listing 4.2: Identifying Brands of PneumoConj Vaccine

```
PREFIX obo: <http://purl.obolibrary.org/obo/>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>

SELECT DISTINCT ?brand WHERE {
?vaccine ?p "pneumococcal vaccine" .
    FILTER (?p IN (obo:IAO_0000118, rdfs:label)) .
?subclass rdfs:subClassOf ?vaccine .
?subclass rdfs:label ?brand .
}
```

RFID reader in the freezer with the reader externally positioned. I then placed the sensors in the freezer and recorded the reads from the sensors. Concurrently, I used DTU6005 DirecTemp USB thermometer to monitor and log the temperature. The experimental set-up is illustrated in Fig 4-6.

I conducted two experiments to establish and refine the performance of the sensors. In Experiment 1, I characterized the sensor performance by limiting variability in sensor fabrication and deployment. The six 2mL screw vials chosen from a low-cost commercially available pack for Experiment 1 measured within 1.5 standard deviations of their length and maximum outer diameter. Using the fabrication method described above, I transformed these vials into sensors and placed them in the freezer. Additionally, I ensured that the freezer was left undisturbed during the time the sensors were being detected by the reader. An incremental improvement in the experiment was our ability to completely expose the metal strip on both sides of the chip on the RFID tag by detaching it from the plastic base. The exposure enabled me to attain higher yield of sensors from the vials. Fig 4-7 illustrates the time to breakage of the six sensors tested in the experiment. All the six sensors detected freezing in a consistent manner as evidenced by low standard deviation and mean statistics.

Having established the accuracy of the sensor in detecting freezing under standardized conditions, I investigated on-field sensor performance by mimicking a ground scenario. In Experiment 2, I randomly selected six vials as base material for the sen-



Figure 4-6: Experimental Set-up

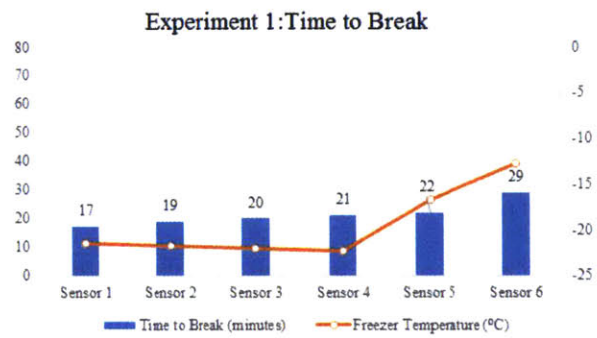


Figure 4-7: Expt.1: Time to Break

Listing 4.3: Identifying Adverse Events Associated With Prevnar

```

PREFIX obo: <http://purl.obolibrary.org/obo/>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>

SELECT DISTINCT ?ae where {
?s ?p ?o
FILTER ( ?p in (obo:IAO_0000118,rdfs:label) )
FILTER REGEX(?o,"prevnar","i")
FILTER REGEX(?o,"associated","i")
?subclass rdfs:subClassOf ?s.
?subclass rdfs:label ?ae
FILTER (!REGEX (?ae, "adverse event", "i"))
FILTER (!REGEX (?ae, "headache", "i"))
FILTER (!REGEX (?ae, "muscle pain", "i"))
FILTER (!REGEX (?ae, "fatigue", "i"))
FILTER (!REGEX (?ae, "arm motion limitation", "i"))
FILTER (!REGEX (?ae, "local swelling", "i"))
FILTER (!REGEX (?ae, "sleep", "i"))
FILTER (!REGEX (?ae, "irritability", "i"))
FILTER (!REGEX (?ae, "appetite", "i"))
}

```

Table 4.2: Comparison of Time to Breakage of Sensors in Experiments 1 and 2

Experiment	Number of Sensors	Time to Breakage (H:MM:SS)			
		Avg.	Min.	Max.	Std. Dev.
1	6	0:21:20	0:17:16	0:29:24	0:04:18
2	6	0:54:28	0:30:29	1:15:07	0:18:21

sors. Additionally, I opened and closed the door of the freezer intermittently to reflect on-field usage. It is important to note that several vaccines, including *Prevnar 13*, are forbidden from being stored in freezers [34]. The behavioral simulation in the experiments is representative of erroneous practices on the ground. The time to breakage of the six sensors is illustrated in Fig 4-8.

It is evident from the data that controlling the variability in sensor fabrication resulted in more consistent data in Experiment 1. Table 4.2 compares the summary statistics of Experiments 1 and 2.

While more uniform dimensions can explain the lower standard deviation in the time to breakage in Experiment 1, it does not account for the prominently subdued

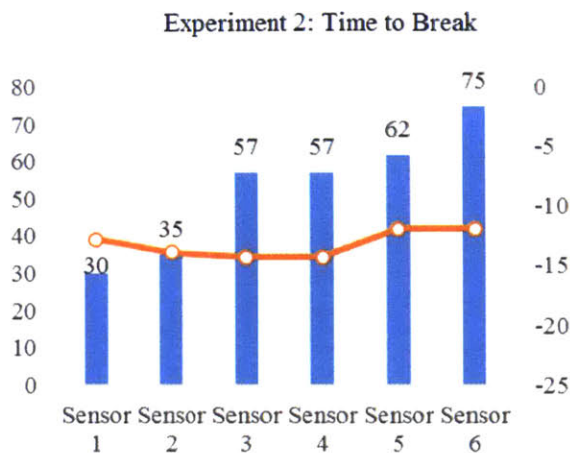


Figure 4-8: Expt.2:Time to Break

mean. The mean shift in Experiment 2 is attributable to the disturbed state of the freezer that fostered frequent spikes in its temperature. The frequent spatial redistribution of heat delayed the rate of freezing of water and consequently, the cracking of the sensor.

The results from the experiments indicate that VacSeen is founded on feasible technological standards and the components of the platform perform as intended. The barcode scan validation system, the record classifier and data connector, as well as the freeze sensor evidence the benefits from application of AIDC technologies to the information systems pertaining to immunization in developing countries. While it is important to enhance the maturity of the platform to render it deployment-ready, a crucial step is to also investigate feasible pathways for such implementation.

Chapter 5

Deployment Guide

It is not an exaggeration to state that developing a technological solution is one of the easier aspects of solving global health challenges such as subpar vaccine access in developing countries. Ensuring continued financial support, engaging key stakeholders, instituting processes on the ground, and scaling up swiftly are important factors for a solution to have sustained and meaningful impact. In developing VacSeen, I made it a point to continually seek feedback from personnel engaged in immunization efforts in implementation and/or decision-making capacities. The feedback proved helpful in not only informing the product development pathway but also engaging the stakeholders as the solution matured.

5.1 Application of Systems Approaches

The engagements with PATH and VaxTrac were critical for the development of the software components of VacSeen. The decision to approach the mentioned organizations stemmed from both acquisition of tribal knowledge as well as formal mapping of the immunization ecosystem in countries where AIDC technologies are being tested in the form of Stakeholder Value Networks (SVN). The SVN of the immunization ecosystem in Benin is depicted in Fig 5-1.

The SVNs of the developing countries where multiple organizations are engaged in enhancing vaccine coverage tend to be similar. The similarity stems from a rather

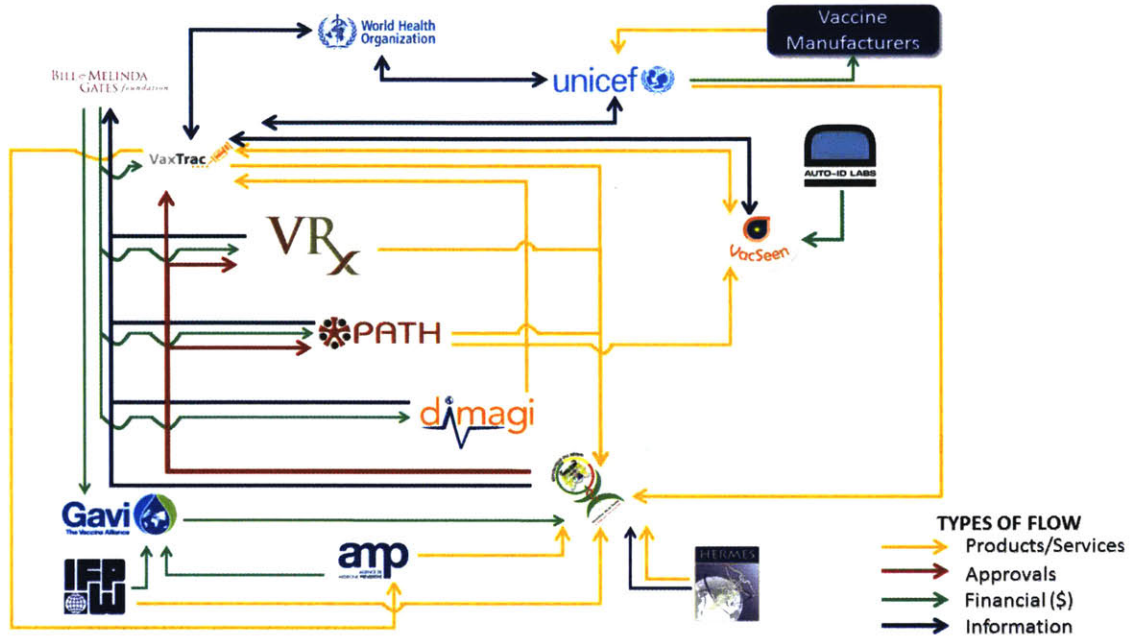


Figure 5-1: Stakeholder Value Network of Immunization Ecosystem - Benin

narrow set of organizations working in the domain of vaccine access and a certain degree of uniformity in the characteristics of the public health systems of such countries. The public health systems in such countries are often characterized by need for external funding to procure adequate quantities of vaccines as well as the need for multiple stakeholders with different competencies to work in tandem with national governments to implement large scale immunization programs.

The SVN of Benin’s immunization ecosystem makes it apparent that VaxTrac is one of the key stakeholders in the country given its relationships with local government, funding agencies, and technology partners. Such details can be visually parsed from the diagram through the density of connectors from an entity representation. Demonstration of VacSeen’s utility in improving VaxTrac’s operations in the country is thus likely to be widely noticed. From a holistic perspective, it is thus a prudent approach to map the ecosystem in which a technological solution is anticipated to operate, and engage the appropriate stakeholders as early as appropriate. The application of systems principles, however, extends beyond the ‘big picture’ overview afforded by tools such as SVN.

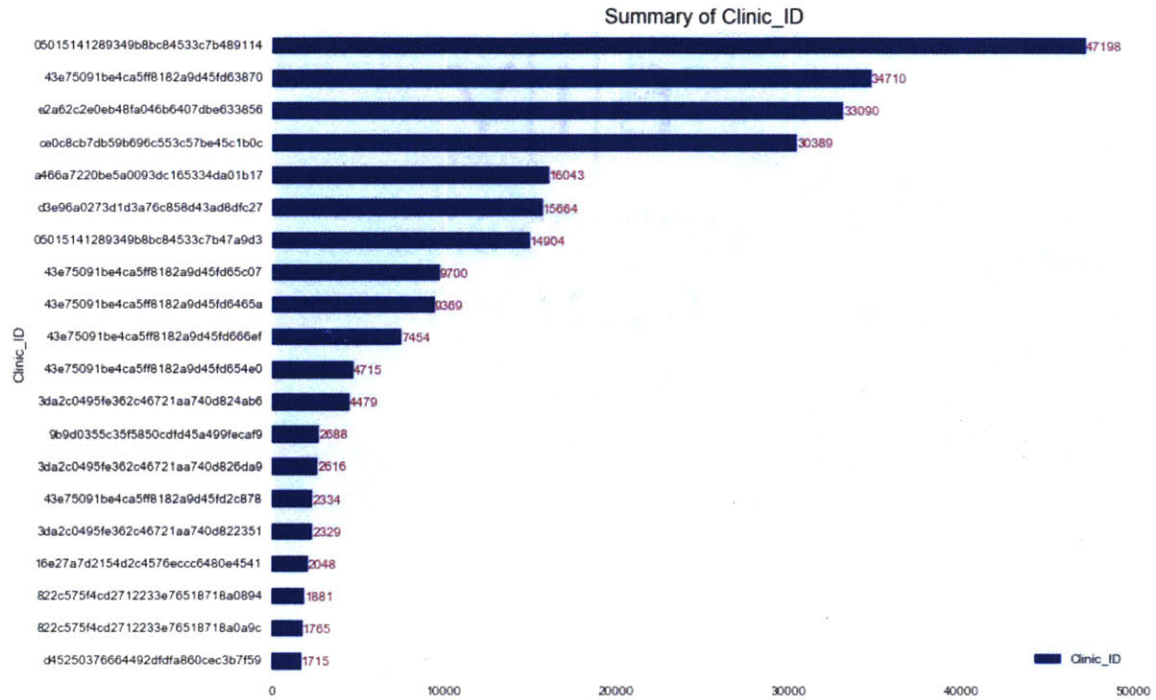


Figure 5-2: Top 20 Clinics Based on Number of Scans

5.1.1 Network Analysis as an Implementation Guide

A natural next step in the evolution of VacSeen is its application in a concerted manner in a Proof-of-Concept (POC) study. Such a study can enable comparison of pre- and post-intervention scenarios with respect to implementation of VOIC-based decision tool described in Section 3.1.2. An important decision for such a study is the selection of sites.

The data shared by VaxTrac reported scans of barcodes on health records of vaccine recipients from 86 clinics. Fig 5-2 depicts the top 20 clinic locations in terms of the number of scans.

It is evident from Fig 5-2 that over 60% of the scans are reported from 10 of the 86 clinics. One can consider one of the clinics with highest scans for the study given the higher likelihood of encountering issues experienced with deploying the classifier and the decision tool in such a setting. Such a selection, however, could potentially exclude ground realities such as recipient mobility from being reflected in the study. The movement of a child from one location to another during its infant months

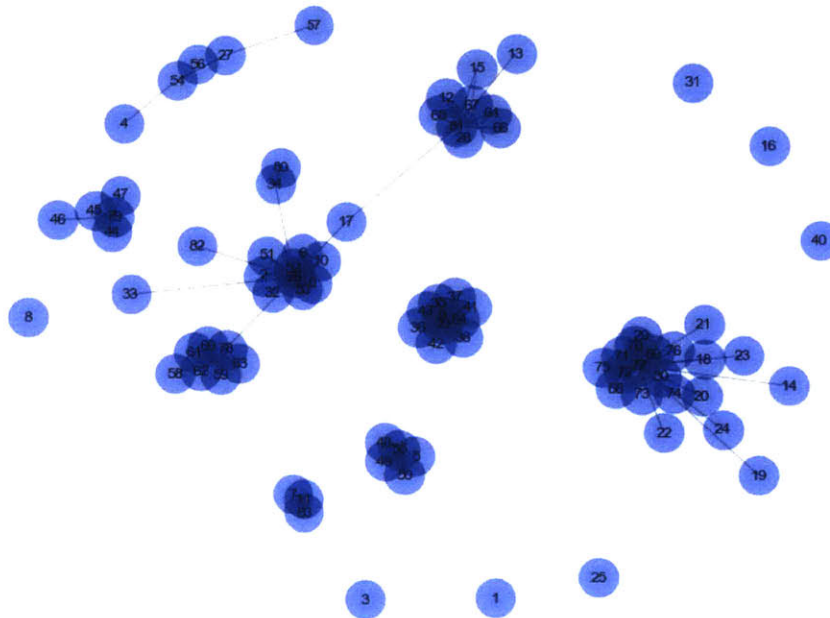


Figure 5-3: Network Representation of Clinics - Benin

is commonplace in several societies because of factors such as social customs (for example, a woman giving birth at her maternal home) and livelihood necessities on its parents (for example, migration for manual labor during non-agricultural season)¹.

The application of network analysis is a particularly useful approach in this context. To accommodate the possibility of the recipient's movement, I considered the clinics where VaxTrac operates as nodes of a network. The edges between two nodes are formed by the number of common recipients between them. Fig 5-3 depicts a representation of such a network and Table 5.1 lists the characteristics of the network.

The 86 nodes of the network represent the clinics. The edges are the common recipients between the clinics. The 9, 161 recipients who visited more than one clinic constitute about 19% of the total of 53,488 recipients whose records were shared by VaxTrac. A study of the effectiveness of VacSeen's classification and decision-enabling

¹Field Observation, Tripura, India, 2013

Table 5.1: Characteristics of Network of Locations

Parameter	Value
Link Density	2.51
Average Degree	213
Cluster Coefficient	0.014
Number of Clusters	14
Nodes	86
Edges	9161
Multiedges	144

tool thus needs to factor in the mobility of the recipients.

The identification of the 14 clusters based on the extent of recipient mobility is useful in choosing the study site. A listing of clinic IDs as per their serial numbers is available in Appendix A.1. The cluster information, when complemented with systemic characterization depicted in Fig 5-4, enables identification of individual nodes (clinics) that are most connected and thus suitable as study sites.

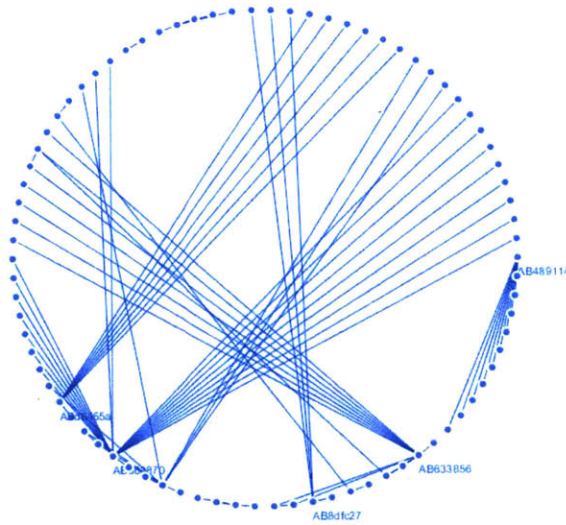


Figure 5-4: Circular Network Representation

It is apparent from Fig 5-2 and Fig 5-4 that the most connected locations also happen to be the ones with highest number of scans. The finding strengthens the case for selection of one of the clusters anchored to high scan density locations for the study. The IDs of the clinics have been abbreviated using 'AB' and their respective last six characters for readability. Deeper information about the nature of relationship that

each clinic has with others in its cluster can be gathered from Fig 5-5.

Fig 5-5, in addition to identifying the clusters, illustrates the strength of the relationship between clinics based on the count of common recipients. It must be mentioned that the number of clusters in Fig 5-5 is reduced compared to Fig 5-3 because clinics with no connections are excluded from the former. The cluster anchored to *AB489114*, the clinic with most scans, is depicted in Fig 5-6.

The network analysis clearly demonstrates the utility of a systemic approach to implementation of technological solutions such as VacSeen at the last mile. It enables capturing the finer nuances that impact the success of an intervention as well as facilitating effective communication of complex technical information to the stakeholders.

The basis for clustering remains to be investigated. While it is likely that geographical proximity of clinics drives the observed clustering, it will be interesting to identify other factors that contribute to the phenomenon. Such analysis will be the features of the subsequent work for expansion of the capabilities of VacSeen.

5.2 Importance of Last Mile Data

The barcode project in Tanzania mentioned in Section 1.5.1 is an effort by the vaccine access community to demonstrate the benefit of deploying AIDC technologies in developing countries. The project, however, does not entail including barcodes at the primary packaging level. VacSeen demonstrates the additional value of incorporating AIDC technologies for tracking the products till the last mile.

The Semantic Web-anchored approach manifest in VacSeen warrants a relook at how the benefits of incorporating AIDC are calculated. The connectedness of the data enabled by the technology facilitates redressal of multiple issues that plague vaccine logistics at the last mile in resource-constrained settings. A Cost-Benefit Analysis, or any other study, that aims to quantify such benefits needs to factor in the multiplicity of problems addressed by such an approach instead of only considering the logistical benefits. An illustration of the spectrum of problems that linkage of data can help solve is depicted in Fig 5-7.

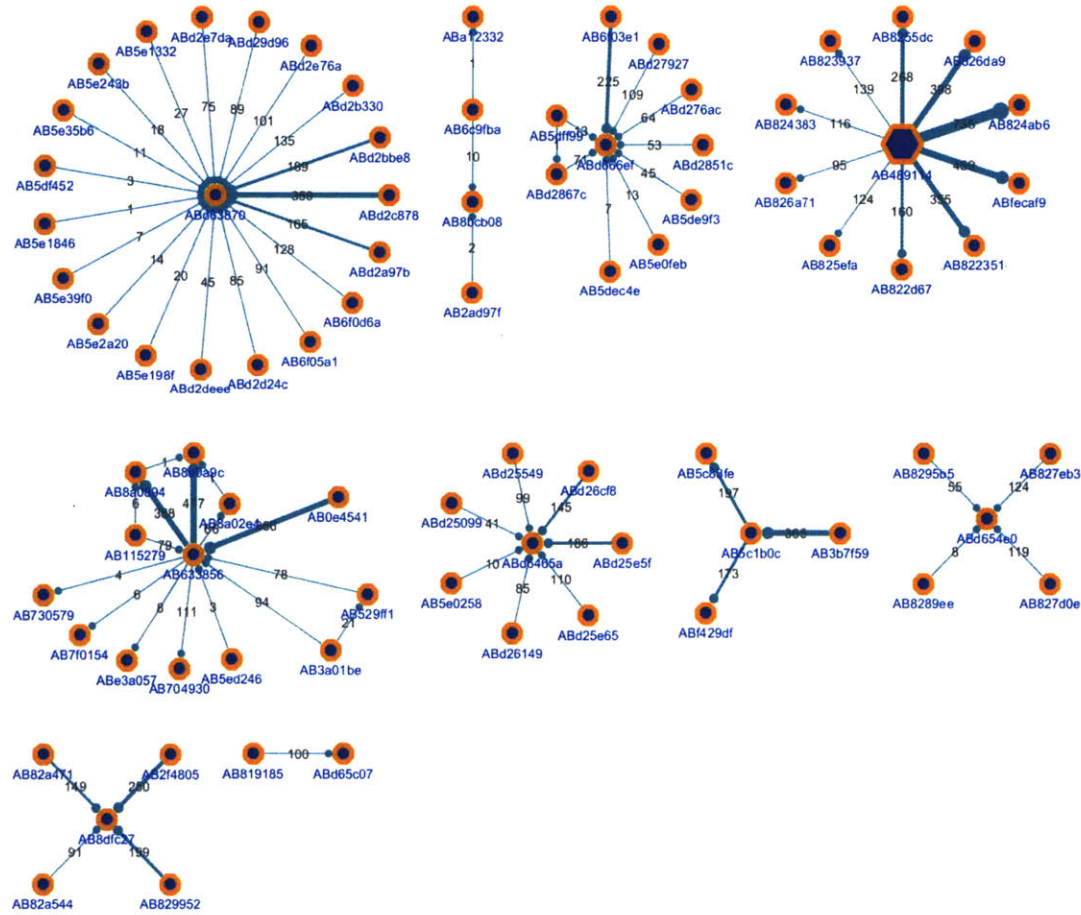


Figure 5-5: Network Representation

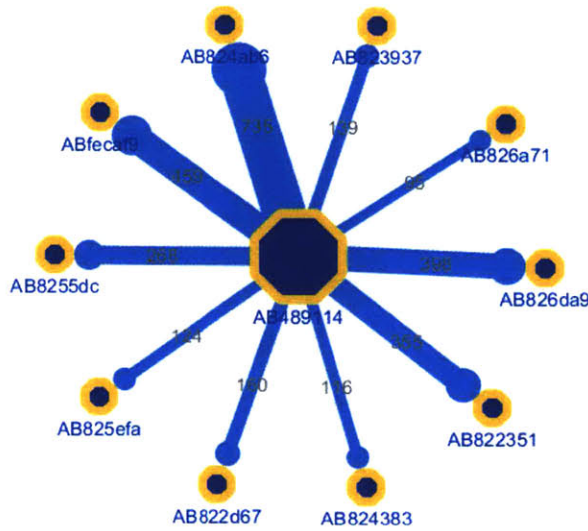


Figure 5-6: Cluster of Locations Anchored to AB489114

Addressing the issue of subpar vaccine access as a multidisciplinary information capture and management issue, instead of a logistical challenge, unlocks diverse avenues for interventions and joint leverage of the solution for multiple beneficial outcomes. Semantic Web is a particularly attractive tool for bringing such a proposition to fruition because of its structural flexibility as well as the ability to abstract over data and information silos. For such an approach to manifest, however, the critical success factor is some degree of uniformity in stakeholders' framing of the problem. The organizations working on various touchpoints of the immunization value chain, be it logistics, behavioral improvement, cold chain management, or product development, need to operate with the cognizance that these steps are interrelated. Consequently, the problems attendant to the touchpoints only propagate, and at times are magnified, if left unresolved as vaccines traverse the path from the manufacturer to a recipient. It is, of course, unrealistic to expect perfect harmony among the stakeholders or the unit operations in the value chain. However, establishment and adherence to common minimal standards, such as agreement on AIDC technology adoption and curated data sharing agreements can go a long way in addressing both common and

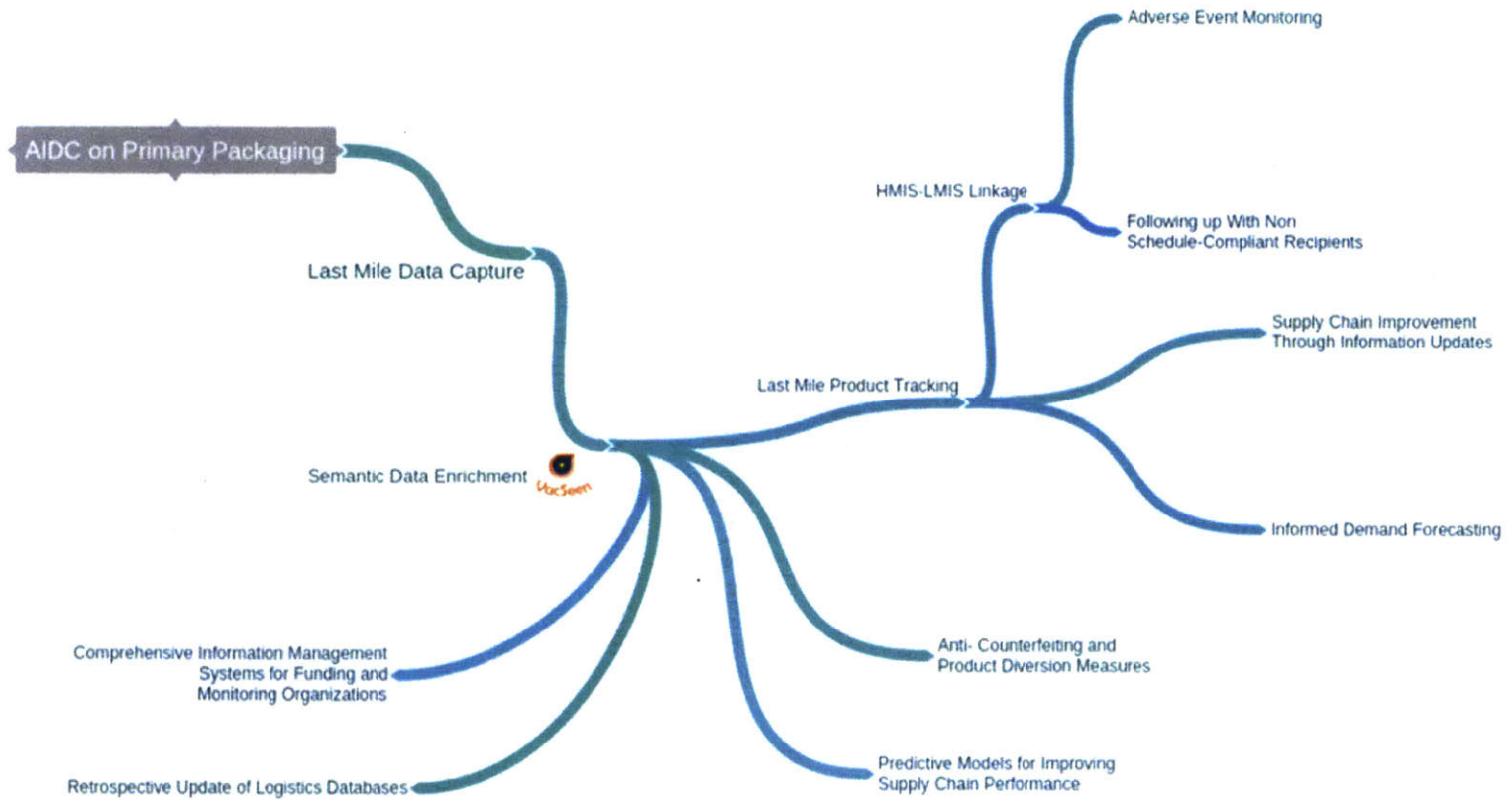


Figure 5-7: Benefits of Last Mile Data

unique issues faced by the stakeholders.

5.3 Technology in and as Policy

The importance of technology in fostering equitable vaccine access cannot be overstated. The issue of subpar vaccine access is, however, not a technological problem in its entirety as detailed in Section 1.5.1. The most effective utilization of technology in this context will be rendered possible when it is contextualized with other relevant aspects of intervention such as policy, communication, and economics. I relationally map technology with other components by taking VacSeen as an example.

For VacSeen to be effectively deployed, it needs to be adopted and sustained by a wide community of global health practitioners. Tools such as OpenLMIS, OpenMRS, and DHIS2 owe their relative success in the global health space to such adoption. Such adoption is likely to be natural when driven by 'pull' factors instead of being 'pushed' onto the immunization community. The two key 'pull' factors in VacSeen's context are utility-driven consumer demand and its adoption through a policy recommendation. In case of the latter, the tool is still 'pushed' onto the practitioner community because of a policy mandate. The likelihood of success of the tool is consequently reduced.

The ideal road to deployment for VacSeen is thus striking a balance between satiating consumer needs and demonstrating adequate value to pique the interest of policy formulators and funding bodies. VacSeen's ability to meet consumer needs is primarily a technology and user experience challenge with limited applicability to the policy context. The demonstration of its value proposition to decision-making bodies is, however, as much a policy challenge as anything else.

Effective contextualization of VacSeen to the policy landscape is hinged on first generating a functional understanding of the latter. The SVN in Fig 5-1 illustrates the engagement of most major stakeholders in the immunization ecosystem with the efforts in Benin. Policy making for immunization access in developing countries has typically followed the traditional or linear policy cycle comprising agenda-setting, policy formulation, implementation, and evaluation. Advancement in problem un-

derstanding and evolution of technology and policy landscapes has resulted in more mature policy formulation and analysis frameworks. The adoption of AIDC technologies lends itself particularly well to the 'Multiple Stream Model' proposed by Kingdon from a policy standpoint [26]. The confluence of problem, politics, and policy in the context of vaccine access has opened a 'policy window' to push technological reforms. The window is evidenced by the 'Decade of Vaccines' initiative discussed in Section 1.5.2. It is imperative for solutions such as VacSeen to make use of this window to facilitate policy reform such that technological adoption becomes a natural choice in efforts to improve vaccine access in resource-constrained settings.

The key policy lever that technology needs to anchor itself to is its strong coupling to outcomes. The international development community in general and the global health community in particular has realized that channeling funds without planning and oversight is not particularly effective in solving developmental problems on the ground. Donors and policy organizations thus increasingly exhibit pronounced proclivity to 'evidence-based funding'. The singularly distinctive feature offered by technology-based solutions is their amenability to monitoring and evaluation.

In such a scenario, technology can be mapped to policy in two ways. First, becoming synonymous as agents for outcomes assessment, and consequently a key parameter for meeting prerequisites for funding, will ensure adoption of technology itself as policy. For instance, VacSeen's ability to identify non schedule-compliant recipients is a feature that can be naturally harnessed by interventions such as VaxTrac's that capture data on the ground. Appending the former as a monitoring and evaluation tool in addition to a decision-making one as described in Section 3.1.2 remarkably blurs the distinction between technology and policy. The intersection of technology and policy domains will in turn ease the adoption barriers to former and promote holistic interventions that entail deployment and monitoring instead of one of the two as is often the case today. The second aspect of relevance of technology to policy is at a more macro level.

Key stakeholders increasingly realize that traditional approaches are inadequate to overcome the stagnation in the vaccine access levels in developing countries [36].

Innovative approaches are thus being called for to solve the challenge. Technology is considered synonymous with innovation in contemporary parlance across several disciplines. From a policy standpoint, technology as a discipline has lessons that can inform other aspects of vaccine access. For instance, the evolution of Semantic Web standards proved to be deviant from that envisaged by its pioneers resulting in the latter having to realign their perspective and redirect the evolution of technological standards and their adoption². Demonstration of such flexibility when faced with uncertainties such as impact of data linkage, on the part of the vaccine access community, will be important for the success of interventions. As technologists engaged in enhancing vaccine access we must take it upon ourselves to extract transferable lessons from the discipline to inform the policy-making process. There has never been a better time for such an effort given the pronounced willingness of the stakeholder community to embrace technology and innovation³.

5.4 Future Work

"This is not fair. We have six children and all of them have been vaccinated except the twins. My wife went to the hospital but no vaccines were available that day, and she came back home. Then she was involved in daily activities and forgot to bring the children back to be vaccinated." - Father of a Polio-afflicted child in Benin⁴

The goal of VacSeen is to eliminate, for good, the causes for such statements. A tool such as the classifier discussed in Section 3.1.2 would have helped protect a life from such agony.

The future development of VacSeen will be along multiple axes as depicted in Fig 5-7. My immediate goal is to scale the classifier and product linkage tool to perform a proof of concept study in collaboration with VaxTrac in Benin. The results from network analysis described in Section 5.2 will be useful in site selection based on the availability of VaxTrac's resources. The outcomes from the study will be

²<https://www.youtube.com/watch?v=oKiXp02rbJM>

³<https://sethberkley.wordpress.com/2013/02/20/ted-challenge-tracking-tracing-vaccines-in-the->

⁴http://www.unicef.org/health/benin_48467.html

important for demonstrating the utility of both last mile data and Semantic Web standards to the key stakeholders.

From a long term perspective, I foresee the maturation of VaxTrac into a platform with modular suite of tools that can be deployed across settings with minimal reconfiguration requirements. The common theme across the tools will be their utility in improving last mile vaccine access in developing countries. Potential avenues in the software space include expansion of classification ontologies for schedules of multiple countries, coverage of more product information, and development of models for improving logistical performance. From the hardware perspective, I will investigate the feasibility of extending the sensor capabilities to heat sensing and performing field tests to assess its performance.

Bono, in the foreward to *The End of Poverty* states

"We can be the generation that no longer accepts that an accident of latitude determines whether a child lives or dies. But will we be that generation?" [43]

VacSeen is my effort to help answer that question with resounding affirmation.

Appendix A

List of Clinics

Table A.1: List of Clinics

Number	Clinic ID	Number	Clinic ID
1	AB0e4541	44	AB826a71
2	AB10d5b5	45	AB826da9
3	AB115279	46	AB827d0e
4	AB254a14	47	AB827eb3
5	AB2ad97f	48	AB8289ee
6	AB2f4805	49	AB8295b5
7	AB3a01be	50	AB829952
8	AB3b7f59	51	AB82a471
9	AB47a9d3	52	AB82a544
10	AB489114	53	AB8a02e4
11	AB529ff1	54	AB8a0894
12	AB5c1b0c	55	AB8a0a9c
13	AB5c83fe	56	AB8bcb08
14	AB5de9f3	57	AB8dfc27
15	AB5dec4e	58	ABa01b17
16	AB5df452	59	ABa12332
17	AB5dff99	60	ABd25099
18	AB5e0258	61	ABd25549
19	AB5e0feb	62	ABd25e5f
20	AB5e1332	63	ABd25e65
21	AB5e1846	64	ABd26149
22	AB5e198f	65	ABd26cf8
23	AB5e243b	66	ABd276ac
24	AB5e2a20	67	ABd27927
25	AB5e35b6	68	ABd2851c
26	AB5e39f0	69	ABd2867c
27	AB5ed246	70	ABd29d96
28	AB633856	71	ABd2a97b
29	AB6c9fba	72	ABd2b330
30	AB6f03e1	73	ABd2bbe8
31	AB6f05a1	74	ABd2c878
32	AB6f0d6a	75	ABd2d24c
33	AB704930	76	ABd2deee
34	AB730579	77	ABd2e76a
35	AB7f0154	78	ABd2e7da
36	AB819185	79	ABd63870
37	AB822351	80	ABd6465a
38	AB822d67	81	ABd654e0
39	AB823937	82	ABd65c07
40	AB824383	83	ABd666ef
41	AB824ab6	84	ABe3a057
42	AB8255dc	85	ABf429df
43	AB825efa	86	ABfecaf9

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