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Assessing stability and performance of a digitally enabled supply chain: *Retrospective of a pilot in Uttar Pradesh, India* ☆

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ABSTRACT

Background: Immunization supply chains in low resource settings do not always reach children with necessary vaccines. Digital information systems can enable real time visibility of inventory and improve vaccine availability. In 2014, a digital, mobile/web-based information system was implemented in two districts of Uttar Pradesh, India. This retrospective investigates improvements and stabilization of supply chain performance following introduction of the digital information system.

Methods: All data were collected via the digital information system between March 2014 and September 2015. Data included metadata and transaction logs providing information about users, facilities, and vaccines. Metrics evaluated include adoption (system access, timeliness and completeness), data quality (error rates), and performance (stock availability on immunization session days, replenishment response duration, rate of zero stock events). Stability was defined as the phase in which quality and performance metrics achieved equilibrium rates with minimal volatility. The analysis compared performance across different facilities and vaccines.

Results: Adoption appeared sufficiently high from the onset to commence stability measures of data quality and supply chain performance. Data quality stabilized from month 3 onwards, and supply chain performance stabilized from month 13 onwards. For data quality, error rates reduced by two thirds post stabilization. Although vaccine availability remained high throughout the pilot, the three lowest-performing facilities improved from 91.05% pre-stability to 98.70% post-stability *($p < 0.01$; t-test)*. Average replenishment duration (as a corrective response to stock-out events) decreased 52.3% from 4.93 days to 2.35 days *($p < 0.01$; t-test)*. Diphtheria-tetanus-pertussis vaccine was significantly less likely to be stocked out than any other material.

Conclusion: The results suggest that given sufficient adoption, stability is sequentially achieved, beginning with data quality, and then performance. Identifying when a pilot stabilizes can enable more predictable, reliable cost estimates, and outcome forecasts in the scale-up phase.

1. Introduction

1.1. iSCM context

Strong vaccine supply chains assure that children have access to the right vaccines, at the right time, in the right place [1]. A logistics management information system (LMIS) provides data on vaccine supply and demand, which is used to reach more children with greater efficiency. Unfortunately, LMIS's today suffer from incomplete and delayed data entry, poor data quality, and lack of use [2,3]. Thus, health systems aren't reliably successful in reaching children.

Digitization can improve LMIS via standardized data collection, quick data transmission throughout the system, error reduction,

Abbreviations: CCH, Cold Chain Handler – individual at a health facility assigned to managing the cold chain; CCP, Cold Chain point – facilities that both give immunization sessions and distribute vaccines (not district stores); GPRS, General Packet Radio Service – a packet oriented mobile data service of higher quality than SMS; ITSU, Immunization Technical Support Unit – the agency that implemented the pilot program; J2ME, Java 2 Platform, Micro Edition, which is used to build software for basic feature phones; LMIS, Logistics Management information system; SMS, Short Message Service – a mobile text messaging service; SOP, Standard operating procedure; VCCM, Vaccine Cold Chain Manager – individual at the district level overseeing cold chain in entire district; WiFi, wireless networking technology using radio waves to transmit information.

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and automated reports that elucidate the best course of action [4–8]. Although many users shift easily to digital systems, those with lower literacy or inexperience with digital devices may struggle to adapt, or resist digitization if it results in increased accountability or workload [5–7,9]. Poor network connectivity and lack of electricity also pose challenges [5–7,10–12].

1.2. Context of the Uttar Pradesh pilot

With an annual birth cohort of 5.37 M, and 63.2% coverage of 3rd dose DTP vaccine (DTP3), Uttar Pradesh has more under-immunized children than any other state in India [13,14]. The majority of its population (77.7%) resides in rural areas [14]. Immunization efforts in the pilot districts of Bareilly and Shahjahanpur are below the state average, reaching 53.8% and 49.9% of their annual birth cohort, respectively, with DTP3 [13]. Each district receives vaccines from state level stores, and allocates these to cold chain equipped facilities (CCPs) throughout the district (23 in Bareilly, 16 in Shahjahanpur). On immunization session days, CCPs host sessions, and also supply downstream sites lacking cold storage. During the pilot, both districts administered seven vaccines in the routine immunization program: DTP, Tetanus Toxoid (TT), Bacilli Chalmette Guerin (BCG), Hepatitis B (HepB), Oral Polio Vaccine (OPV), Measles (MCV) and Japanese Encephalitis (JE).

Prior to the pilot, vaccine replenishment in Uttar Pradesh was ad hoc, as was generally the case throughout India [15]. Health workers and district supervisors administering the cold chain had neither formal title nor technical formation. Vaccine inventory was tracked via homemade registers documenting inventory balance, consumption and wastage. Replenishment plans and standard operating procedures (SOP's) existed, but were rarely enforced, resulting in disjointed movement of vaccines from state to district to health facility [15].

Immunization Technical Support Unit (ITSU) orchestrated a digital supply chain information system pilot, with the aim of demonstrating reliable vaccine availability throughout the region. The program ran from March 2014 to September 2015, and included three interventions:

1. **Standardization of data collection *(process)***: Simple paper recording tools to tabulate stock utilization for a given session, and generate outputs for digital data capture.
2. **Real time inventory visibility via digital LMIS *(product)***: Mobile/web software working seamlessly across devices (Java handsets, smartphones, tablets, and desktop computers), operating systems (Windows, Android, J2ME), browsers (Chrome, Safari, Internet Explorer), transmission channels (WiFi, GPRS, SMS), and connectivity scenarios (synchronous, asynchronous, and offline caching/synching). The software was previously deployed to improve vaccine availability in Karnataka in 2012 [10].
3. **Strengthened human capacity (*people)***: Introduction of accountable district level staff – Vaccine Logistics & Cold Chain Managers (VCCM's) – overseeing the cold chain and managing stock across facilities to prevent over and under stocking.

ITSU designated incumbent, CPP level health workers overseeing vaccine supply as Cold Chain Handlers (CCH's), and provided them one day of training. During training, CCH's received new, standard paper forms, SOP's for future reference, and a basic feature phone (Nokia 206) to report aggregate data into the digital LMIS. No refresher trainings occurred after March 2014, and the four VCCMs who joined following this period got the same training with slightly improved materials based lessons from the previous training. More information on these interventions are available in Appendix I.

This retrospective investigates how long it took for supply chain performance to stabilize after pilot launch, and how supply chain performance differed before and after stabilization. In particular:

- **Adoption:** Were access, timeliness and completeness rates sufficiently high to assess data quality and performance? Were rates on par with other digital information system deployments, taking into account the differing contexts of deployment [3,6,16]?
- **Quality:** When did known error rates[1] stabilize, and at what rate? Was the final known error rate comparable to those observed in other deployments [8,17]?
- **Performance:** When did vaccine availability stabilize, and at what rate? How did performance vary across facilities and materials?

Stability has many definitions within supply chain literature, but often includes the concepts of a constant equilibrium and reduced volatility. In this study, we chose *Choucri* et al.'s definition of stability [18], with additional criteria for volatility: "A state is stable to the extent that its resilience is *both* greater than the load exerted upon it [constant equilibrium], *and able to temper volatility*".

2. Methods

2.1. Data collection, metrics and analysis

All data were collected via digital LMIS users, as part of their routine operations (see Appendix II), and hosted on a secure password-protected server. Analysis was conducted on computers provided by the authors' employers, using Microsoft Excel and R (version 3.2.3) and stored in secure hard drives and cloud sites.

Table 1 outlines the adoption, quality, and performance indicators used for the analysis. For the latter two metrics, analysis began with identifying the point of stability. Empirically, stability was defined as:

$$Y = bx + k + e$$

where Y equals rate of performance, x equals time, b equals constant change in equilibrium over time, k equals constant equilibrium value, and e equals coefficient of variation for a given set of x values.

Because supply chains vary widely, there are no single values of b or e that will universally fit all models. In reviewing the structure and behavior of Uttar Pradesh's vaccine supply chain, performance converged noticeably when:

- $|b| < 0.01$ for at least 6 months,
- $e < 0.01$ for at least 6 months.

Thus, for this study, we used these rules for b and e to define a stable state.

After identifying the starting point of a stable sate, average performance before and after stability were compared using a t-test to determine whether the system improved once stabilized. Performance differences across materials were calculated using a chi-squared test.

2.2. Limitations

There were no control group districts and due to the fragmented, ad-hoc, non-standard paper based prior system, this study was not able to capture a true baseline in the two pilot districts.

[1] Known error rates refer to the subset of total errors that are capturable (e.g. invalid entries in this study, formatting errors in other studies, etc.) These are not comprehensive error rates as they do not capture incorrectly entered data that is an acceptable value for the system.