Improving Performance of Rural Supply Chains Using Mobile Phones

Reducing Information Asymmetry to Improve Stock Availability in Low-resource Environments

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ABSTRACT

Ensuring availability of essential goods, such as medicines or vaccines, at the point of care in the villages is a significant challenge in rural supply chains. The crux of the problem lies in information asymmetry of supply and demand, as well as *ad hoc* distribution practices. These supply chains are not managed efficiently, and often information flows upstream in the chain in an incomplete, incorrect and untimely manner. This ultimately affects procurement and distribution decisions, consequently leading to stock outs of important goods at the point of care.

To address the problem of stock availability, we have implemented a "Bulletin Board" that digitally captures needs (demand) and availability (supply) of goods in real-time from any location using low-end mobile phones, and broadcasts this information to vendors and managers, upstream in the supply chain. We demonstrate that *by reducing information asymmetry between supply and demand, the overall system "self-organizes" in a manner that stocks are appropriately re-distributed*, thereby improving availability at the point of care. We demonstrate these concepts in the context of vaccine and medicine availability in a public health supply chain. In a study in Karnataka, India, we have observed vaccine stock availability increase to 99% and replenishment responsiveness improve by 64%. However, such an approach relies on obtaining high quality of data from the last mile, which is a big challenge in low-resource environments, where mobile networks are unreliable and human capacity is low. We describe the design of a mobile phone based service that leverages insights from *information asymmetry theory* and effective *service design* to achieve sustainable supply chain performance in low-resource environments.

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H.4.3 [**Information Systems Applications**] Communications Applications – Bulletin Boards; H.1.2 [**Information Systems**] User/Machine Systems – human factors, human information processing; J.3 [**Computer Applications**] Life and Medical Sciences – Medical Information Systems; K.4.3 [**Computers and Society**] Organizational Impacts – Computer-supported collaborative work.

General Terms

Management; Measurement; Performance; Design; Economics; Reliability; Experimentation; Human Factors.

Keywords

Mobile phone application; bulletin board; supply chain management; information asymmetry; rural supply chain; public health.

1. INTRODUCTION

Many villages in developing countries do not have adequate or timely access to vaccines and essential medicines [19]. Villagers travel long distances to procure them, or have to find more expensive alternatives, thereby contributing to poor health conditions in rural areas [3]. The crux of the "availability problem" lies in: (a) limited visibility into demand from the PHCs, (b) unpredictable supply patterns from higher-levels in the supply chain, and (c) poor management capacity amongst health workers at the PHCs (which is the last-mile in the health supply chain). This leads to disconnectedness and operational discord between people in different echelons of the supply chain. This, in turn, results in sub-optimal stocking and replenishment behavior, and consequently diminishing stock availability at the last-mile.

Essentially, what we are witnessing here are conditions prevalent in *low-resource environments*. A low-resource environment is one where there is (a) a restricted information network, and (b) human capacity is low (on management discipline and technology usage).

Traditionally, the stock 'availability problem' in supply chains has been addressed using inventory transaction data, such as sales or receipts, from each node in the supply chain, and *optimizing* stock quantities and delivery schedules for a given material using optimization algorithms [8]. Such methods rely on transactional data of reasonable volume and quality, acquired in a sustained manner over a period of many months. This is quite feasible in high-resource environments, whereas it is a huge challenge in low-resource environments. Low human capacity for using web or mobile-phone applications, lack of stock management discipline and unreliable mobile or wired networks make it difficult to get continuous data for effective forecasting or optimization.

Our approach to addressing the availability problem is quite different. Rather than optimizing stock quantities at each node, we simply aim to offer real-time visibility into stock supply and demand across the supply chain network, thereby enabling people to "self-organize" to redistribute stock. This reduces the quantum of data required for decision-making, and diminishes the need to rely on a hierarchical, top-down management structure. Our hypothesis was that *reducing information asymmetry between supply and demand enables people in a low-resource network to self-organize to achieve goals*. We have found evidence in Karnataka's public-health rural supply chain network, that people *do self-organize* to improve stock availability, if visibility is provided in a *timely* and *usable* manner. We believe that this approach can be extended to any low-resource environment that relies on data-driven decision making.

In this paper, we first provide some context to our low-resource environment and the challenges inherent to it (section 2). Subsequently, we describe the implementation of a digital "Bulletin Board" that provides real-time visibility into abnormal stock situations in a supply chain network (section 3). We then quantitatively demonstrate changes in human behavior, and the positive impacts on vaccine availability (section 4). We further reflect on related work and indicate why this study is unique (section 5), and finally present our conclusions (section 6).

2. A LOW-RESOURCE ENVIRONMENT

A typical rural, public-health supply chain network is a hierarchical setup, wherein materials flow from National warehouses to State warehouses, then to District/County stores, and finally make their way to the village PHCs. In many respects, the PHC is the last-mile of health service delivery in villages. Vaccines and essential medicines are stored in a pharmacy within the PHC, which is manned by a pharmacist or health worker (such as a nurse). The pharmacist dispenses medicines or vaccines according to the doctor's prescription, and typically performs the following kinds of transactions: (a) issue goods to patients, (b) raise orders to replenish depleting stock, (c) receive goods delivered to the PHC and re-stock them, (d) count physical stock on shelves on a periodic basis for record keeping, and (d) discard damaged or expired goods. Figure 1 illustrates the flow of goods across the supply chain and the transactions at each node in the chain.

The personnel at the PHC traditionally record transactions in physical registers. In addition, they now use an application on a low-end mobile phone to enter transaction data, while people upstream in the chain use a web browser on a computer to monitor and manage.

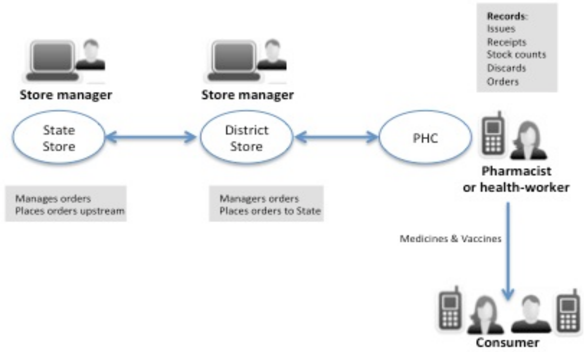

Figure 1. Rural supply chain for medicines and vaccines

Based on the data entered at the PHCs, people upstream in the supply chain (i.e. suppliers) now have a real-time visibility into stock availability or abnormal stock conditions at the PHCs. Consequently, the expectation is that appropriate replenishment decisions will be made in a timely manner, thereby reducing stock-out or low-stock situations. However, there are significant barriers to achieving a reliable, real-time decision support system in a low-resource environment, because acquiring high quality data from the last-mile is a significant challenge.

2.1 Challenges

There are several problems and constraints in a low-resource environment that lead to poor performance. In the supply chain context, it leads to frequent stock-outs of important goods at the point of care. The challenges are described in more detail in [16], but the relevant ones are summarized here.

1. **Human challenges**: PHCs are grossly understaffed, which results in overburdening existing staff or imposing the same duties on less qualified individuals. Staff members do not always have the capacity to use technology, be it computers or mobile applications. Adequate management and communication skills are often lacking amongst staff, and a culture of cooperative problem solving is lacking between PHC and district-level staff. Upstream in the supply chain, supervisory capacity is limited, making it difficult to act on information, even if it was available in good measure. These factors lead to inconsistent and incorrect book keeping, and consequently poor stock management. In certain cases, unethical practices by managers drive procurement decisions upstream in the supply chain, which leads to suboptimal replenishment at the PHCs.

2. **Technical challenges**: Internet (GPRS) networks are largely unreliable or unavailable at the point-of-care, thus making data entry through the mobile devices a challenge. This is especially true in transaction-intensive contexts, where hundreds of goods must be managed on a daily basis. SMS or USSD based mechanisms are not sufficient to collect reliable data in these environments. This leads to a degraded data-entry experience, and results in inconsistent entries. Further, heterogeneity in low-end phone models is significant, making it challenging to support applications seamlessly across devices.

3. **Environmental challenges**: There are infrastructural constraints that inherently limit supply chain performance. Poor roads result in long delivery lead times. Absence of computerized systems leads to information delays, which magnify uncertainty along the supply channel. These factors manifest themselves as a *bullwhip effect* [10], wherein small distortions in demand at the last-mile, propagate upstream in an amplified form. Information asymmetry between supply and demand results in: (a) chronically poor forecasting, (b) inaccurate procurement at higher echelons, (c) reactionary or *ad hoc* delivery patterns, and (d) suboptimal stocking and replenishment practices. In addition, transportation routing and scheduling are inefficient, leading to delayed delivery or pickup.

These challenges pose a significant barrier in achieving appropriate adoption of mobile applications in the last-mile, and consequently make it difficult to achieve data-driven decision-support upstream in the supply chain. To reduce 'information asymmetry', we first need to address the low 'data quality' problem in low-resource environments.

We describe a Bulletin Board system, which incorporates simplified interaction protocols and a robust data collection mechanism using mobile phones [2], to achieve real-time information visibility between supply and demand nodes, thereby reducing information asymmetry in the network. We further demonstrate how this system changes behavior amongst participants towards achieving better supply chain performance.

3. BULLETIN BOARD

Supervisors and district-level health officials tend to be extremely busy, performing multiple roles and tasks, and often do not have easy access to computers and Internet at the district office. Even otherwise, the capacity to use web applications is not strong with many supervisors. Given this, their bandwidth to consume web or email reports and detect inventory problems is quite low. Supervisors typically become aware of inventory problems at a PHC only much later, if the pharmacist brings it to their attention, or when the problem has become big enough to be noticed. A culture of promptly calling supervisors to report inventory problems did not exist at the PHCs. Further, an SMS notification to the supervisor did not always motivate action, especially when he was handling several other higher priority tasks that were assigned to him. Essentially, we needed a notification mechanism that has redundancy in viewership, and consequently exerts some "social" pressure to act.

The Bulletin Board is a dynamic HTML page on a web browser that continuously streams abnormal events, such as out-of-stock, low-stock, excess stock, user inactivity at a node, and so on. The message stream is rendered on a television or a large-screen monitor strategically mounted on a wall in the supervisor's office or a public space. Figure 2a shows a Bulletin Board placed at a monitoring center in Bangalore, Karnataka.

Each event on the Bulletin Board includes the type of the event (e.g. low-stock), its location, the time of occurrence and a contact number to call, as shown in Figure 2b.

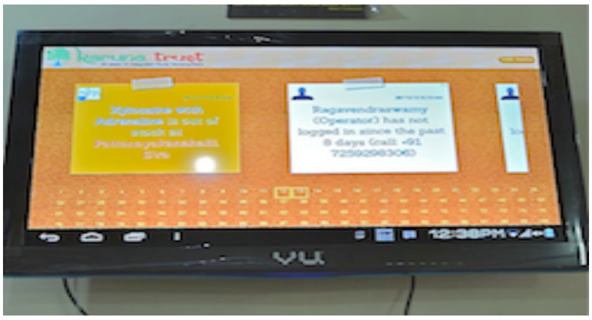

Figure 2a. Bulletin Board installed in the field

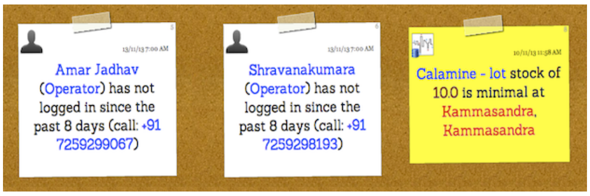

Figure 2b. Events on a Bulletin Board

These events are derived from transactional data entered through the mobile application by health workers at the PHC, which directly affect stock quantities at that location. For instance, 'issues' or 'discards' deduct the stock quantity of a given material, while 'receipts' increase it. It should be noted that this data is *transactional* in nature, and has to be reliably handled by the system to ensure data integrity. Based on historical patterns, minimum or maximum stock levels are set for items at each facility. Using these thresholds, supervisors can be alerted to under-stock or over-stock conditions at the PHCs. Further, we allow anyone to post unstructured text messages to communicate local constraints that cannot be easily derived from the transactions. Motivational messages that highlight good performers are also streamed, so that it encourages the community, as a whole, to perform better. Messages posted to the Bulletin Board are also transmitted over SMS to all subscribers. In this fashion, all negative and positive events are visible to all subscribers in the network, either through the Bulletin Board or their own phones.

3.1 Characteristics

The Bulletin Board essentially captures and presents abnormal and critical events in the environment, in a manner that can be quickly consumed. It has a few salient characteristics that make it *actionable* in an environment with low supervisory capacity:

1. By keeping the nature of information simple and concise, it is easy to consume by everyone. It replicates a natural model of a physical bulletin board, on which one pins Post-it notes.
2. By virtue of being in a public space, it exerts an element of "social pressure" or "social status", motivating people into action.
3. It is continuously visible to multiple people, thereby enabling redundancy in problem detection and resolution.
4. By keeping the data lightweight, it loads well even in environments with low network-bandwidths.

Once prompted into action, the supervisor can delve deeper into a browser-based management console using his laptop or tablet. We demonstrate that a simple mechanism of information exchange, as described in this paper, changes behaviors towards timely replenishment actions, thereby improving availability at the last mile. This model can also be opened out to all the PHCs in the network, thereby facilitating true self-organization of the supply chain based on real-time stock information. Actions to resolve problems could involve one or more of the following:

a) Timely delivery/pickup of stock from the warehouses to the correct locations.

b) Pre-emptive procurement at higher echelons in the supply chain, in a timely manner.

c) Transfer of stocks from an over-stocked location to an under-stocked location.

d) Budget reallocation and provisioning alternate supplier channels.

In strongly hierarchical supply chains, typically the person with a problem does not have the solution, and is dependent on upstream managers to resolve it. The Bulletin Board provides an understanding of the problem across all echelons in the supply chain in a consistent fashion. This aligns mental models, leads to increased interactions across the network, and sharing of ideas to solve problems. It further sets correct expectations across the chain on outcomes emerging from management actions.

3.2 System model

Figure 3 illustrates a model of the system underlying the Bulletin Board.

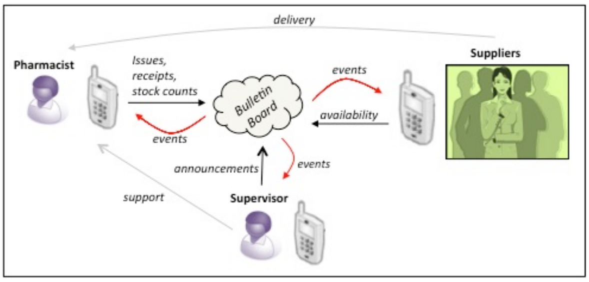

Figure 3. Bulletin Board system model

The system involves the following components:

1. A mobile application (Java 2 Micro-Edition, J2ME) that is installed on the phones of the pharmacists or health workers, with the ability to transmit data over GPRS, SMS or work fully offline [2].

2. A cloud-based logistics software, with ability to reliably collect transaction data over GPRS or SMS, generate events, post them to the Bulletin Board, and send alerts over email and SMS. Wherever sufficient data of good quality is available, probable abnormality events are generated by automatically computing safe stock levels – based on consumption patterns and forecasting as done in [4].

3. A web-browser based Bulletin Board and a management console that is available to supervisors and suppliers.

As seen in Figure 3, the pharmacists enter transactions – issues (or sales), receipts, discards (of unusable goods), and stock counts using their mobile phones. These data are aggregated over the cloud, and relevant events are generated and broadcast over the web, email and SMS to all subscribers.

3.3 Solving the 'data quality' problem

The 'data quality' problem mentioned earlier was due to: (a) low human capacity, and (b) unreliable mobile networks in low-resource environments.

3.3.1 The capacity problem

Human capacity is lacking on both stock management and technology usage in these environments. The capacity problem exists at two levels:

1. At the PHC or last-mile, there is typically lack of management discipline or inability to use mobile applications on phones to enter data. Consequently, the data entries are not uniformly good, making is difficult for reliable decision-making upstream in the supply chain.

2. At the higher echelons of the supply chain, such as a District Office, there is a lack of supervisory capacity to analyze and act on a given piece of information within the required time. This leads to inaction over longer periods, and consequently delayed solutions.

These problems have been addressed through *effective service design*. Service design [12] is defined as the activity of planning and organizing people, infrastructure, communication, and material components of a service in order to improve its quality. It addresses the functionality and form of services from the perspective of the users at every echelon of the supply chain. We considered four levels of design as in [14], which include:

1. Design of philosophy or strategy

2. Design of processes and systems

3. Design of user experience

4. Design of features in the product

The above principles were employed within our system in the following ways:

1. *Philosophy and strategy*: The philosophy of design was to reduce the quantum of data from the last-mile required for decision-making. Rather than taking the computational approach of optimizing inventory quantities (as in [8]), which requires a relatively high volume of data of high accuracy, we have strategically leveraged insights from the economic theory of information asymmetry [9] to change behaviors and achieve the same outcomes. This has helped in making effective decisions, even when data was sparse. It is critically important to make design choices at the highest level that reduce the data entry burden on people at the last mile in low-resource environments.

2. *Processes and systems*: A new process of digital data entry and inventory review was introduced across the chain, keeping in mind the capacity constraints at each echelon. The Standard Operating Procedures (SOP) [11] for digital data entry were kept minimal and crisp, and published in local languages, where required. Significant attention was paid to the design of training procedures and materials. Sensitization of stakeholders at every level was as important as training. A top-down supervisory procedure was established specially for stock monitoring using the digital tools provided to supervisors. Social "pressure" and "status" of people were enhanced with appropriate messaging on the Bulletin Board to motivate action.

3. *User experience*: The service design was highly *user-centric*, and factored the needs and constraints of users at every echelon. The time required to perform data entry was minimized. An average of 15 minutes per week was sufficient for data entry at a given location. Further, the mobile interface was simple to help the pharmacist get the job done. Value-added information (such as low-stock or expiry alerts) was pushed to users at PHCs, which helped increase adoption and engagement. Information design was given strong attention, so that the messages were contextual and actionable. Multi-modal communication through voice, SMS and email were employed to effectively reach all participants. Personalized voice broadcasts using web-based voice gateways (such as [5]), were initiated by supervisors as calls for action and to credit people for good performance.
4. *Features*: User interaction with the mobile interface was optimized to the small form-factor, keeping interactions operation-centric, and requiring only numeric entries for transactions. Value-added features were incrementally deployed to the users at all echelons depending on their capacity to consume it. For instance, at the PHCs, the pharmacist's mobile interface was graduated from simple inventory operations (such as issues, receipts, stock counts) to being able to track and manage unsafe stock levels. Similarly, at higher echelons, we evolved the supervisor from detecting problems simply based on abnormal stock events, to troubleshooting problems in the supply chain using additional reports per facility, which were emailed to them. This allowed us to evolve users at every echelon to higher-level features as their capacity and need for information increased.

Service design evolved iteratively, based on feedback from the users at all echelons, and insights gained through our own observations in the field. We performed a one day training session for pharmacists and supervisors, which included a live demonstration and a hands-on session with the mobile phone application – starting with application installation on the phone, application usage, operating procedures for data entry, stock management, error detection and correction. Subsequently, over time, we observed data entry patterns of the pharmacists, isolated abnormal entry patterns, and obtained feedback directly from the corresponding pharmacists over phone to determine the nature of the problems. Based on this feedback, we discussed possible solutions with both supervisors and experienced pharmacists and evolved the application features, standard operating procedures, voice and SMS communication, and customer support methods to the next level of usability.

Through a combination of increased visibility into inventory events upstream in the supply chain and a highly feedback-oriented service to pharmacists, we saw a steady increase in pharmacist capacity to enter transactional data and improved responsiveness to replenish stock on shelves at the PHCs.

3.3.2 The network problem

GPRS networks in rural areas are quite unreliable [6]. In our setup, there are many facilities where GPRS is unavailable or connectivity is intermittent. We observed the following types of problems in such conditions:

1. Unavailability of GPRS at the facility, but availability en route facility to home of the pharmacist.
2. Connection timeouts, wherein the request would reach the server, but the connection times out before the response is received. This prompted pharmacists to try again, leading to duplicate transactions.

These problems have been addressed by leveraging redundancy in transmission protocols, and managing user experience in the event of network failures.

1. The 'GPRS unavailability' problem was solved by enabling seamless switching between GPRS and SMS for data transmission [2], while preserving good user experience on the application. An infrastructure was created on the server-side to manage missing and out-of-sequence SMS messages, so that retries from pharmacists are minimized. More importantly, offline data entry was enabled, wherein the pharmacist could enter transactions offline, and transmit them whenever a GPRS connection became available. For a highly transactional application of this kind, we found that an SMS-based mechanism for transmitting data leads to sub-optimal user experience. Whereas, sending data over GPRS, with an ability to manage data offline on the phone, proved most effective in achieving quality and consistent data entries. This also delivered the best user experience in the event of network failures.
2. The 'connection timeout' problem was solved by de-duplicating transactions on the server side, wherein a fingerprint (message digest) of a set of transactions was created, and compared against the newer incoming sets. If a match was found within a specified duration from the same pharmacist, the transaction set was considered a duplicate and the pharmacist was notified appropriately.

In addition, redundancy of personnel, devices and network carriers was introduced to ensure consistent data entry. This, along with supervisory monitoring, resulted in good data coming from all the PHCs.

3.4 Service Usability

Good usability of all service touch-points is essential to enable adoption of the service by first-time users of mobile applications. There is low tolerance for additional effort or errors in using mobile applications at PHCs, given pharmacists' heavy workload. The cognitive burden on the user has to be managed effectively depending on user capacity.

Strong attention was paid to the usability of the service, including all touch points such as the handheld device, software, documentation, user communication and human interactions (for support). The following aspects were given special attention to achieve good usability.

1. **Device**: The choice of the mobile handset is important to generate a good experience for the pharmacists. Village workers are typically prolific users of feature phones for voice calling, but have rarely used applications on their phones. It is important that the phones have at least a display size of 1.8 inches (such as a Nokia 114), or a more ideal size of 2.4 inches (such as Nokia 206). It is best if the keys on the keypad are separated (not joining each other), and give the finger the feeling of a key-press. This minimizes errors during typing. Further, a simple, highly visible dashboard, such as the Bulletin Board on wall-mounted display, is

adopted more effectively by supervisors and has motivated timely action.

2. **Software**: The software application on the mobile had to be highly usable in the event of intermittent network failures and small screen resolutions.
   a. **User interface**: The user interface was designed to be simple, with the initial screen (after login) showing the operations menu, which allows pharmacists to get the job done. The list of materials could be scrolled vertically, and each entry provided the most important pieces of information in the list entry itself (such as the material name, the current stock and the last updated time). Long material names could be easily perceived through horizontal, animated scrolling of such texts.
   b. **Data loading**: The minimum possible data was loaded from the server that was required to get the user started, with incremental loading in the background. Reconnects to the server to get master data or configuration were minimized through local, persistent caching. The data formats were in JSON with shortened key names to keep the payload low, given GPRS connection timeouts are quite common.
   c. **Error handling**: The most common errors were incorrect data entry and GPRS network timeout errors. It was important that the error messages were crafted in a manner that was easily understood. In the beginning, we noticed that users experienced difficulty understanding an error message that they had not seen before. Putting all the error messages into the user manual was also not a feasible solution, given they could not look those up easily. To make this easy, we opted to transmit error messages from the server, rather than baking the messages in the mobile application. This enabled us to evolve the messages continuously as we better understood user's cognitive abilities, without the need to upgrade the application with every change.
3. **Communication**: Pharmacist interaction was mediated over both voice and SMS. A communication strategy was crafted to encourage good data entry from pharmacists. The SMS messages for data entry reminders or abnormal stock events were crafted in a manner that was actionable, i.e., stating the expected action in addition to the problem. Frequent voice broadcasts from supervisors, elicited positive response from the pharmacists. The communications typically had a positive tone, including expected actions where there were problems and appreciative comments where the management was effective in a given month.
4. **Documentation**: We provided two important documents to users: (1) the user's guide for the application, and (2) a Standard Operating Procedure (SOP) for the process. The user's guide had to be fairly visual with screen shots, and text in local language, where needed. We realized over the early months of usage that some of the errors in data entry or lack of data entry were due to incorrect understanding of the SOP. The SOP had to be fairly crisp, and it took a few iterations with the pharmacists to evolve it to a point where it was very simple and free from ambiguity.
5. **Human touch points**: Human touch points, such as customer support, are most critical in such a system. Support personnel play the important role of helping users at the time of need, but also must build trustworthy relationships with the users. They become the conduit for ongoing understanding of constraints in the user's environment, and building user capacity, where required.
   a. **Support**: Significant attention was paid to phone support, where the support personnel were pro-active, rather than reactive to a call from the user. The support personnel actively called each user who had weak data entry patterns to understand their constraints and build their capacity for data entry. Further, there was continuous feedback on problems faced in the field, be it network errors or usability or new features, that were communicated to the developers. The strong interaction process between field users, support personnel, and developers became instrumental in rapidly evolving the service towards greater adoption.
   b. **Relationship management**: Part of the responsibility was to build a strong trust relationship with users at every echelon in the supply chain. This was achieved through the support calls as well as the refresher training sessions. The trust-based relationship with the service personnel resulted in more open feedback coming back from the community of pharmacists and supervisors, which helped the service evolve faster.

We believe that service usability must be addressed in a holistic manner, rather than just application usability. All service touch points – including hardware, software, documentation and human touch points – have to carefully designed and evolved through continuous feedback to achieve high levels of adoption at the last-mile.

4. IMPACT

An impact study was conducted for 9 vaccines – Bacillus Calmette Guerin (BCG), Diptheria Pertusis Tetanus (DPT), Japanese Encephalitis (JE), Tetanus Toxoid (TT), Hepatitis B, Measles, Rabies, Polio and Pentavalent vaccine – across a sample of 29 PHCs in Karnataka, India. The setup included a Bulletin Board in the management office, wherein supervisors monitored information streaming on a wall-mounted television (as in Figure 2a) and were expected to take actions to resolve stock-outs. The study was conducted on transaction data collected over 14 months starting July 2012, comprising of over 223,011 data points. The transactions included issues, receipts, and stock counts collected across all these facilities per vaccine.

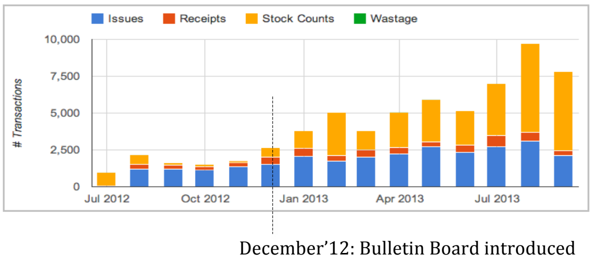

Figure 4. Inventory transactions over the study period

Figure 4 shows a count of the number of transactions entered from the PHCs on a monthly basis. The Bulletin Board was introduced in December 2012, and we can see a steady increase in the number of transactions, in comparison to what were being entered before the intervention[1]. This is because a number of pharmacists became more engaged with the system after receiving feedback from the supervisors or suppliers to help resolve stock-out situations. This clearly indicates that a more public display of inventory problems through the Bulletin Board at a higher echelon (such as district) does trigger stronger action on mobile data entry from the PHCs.

Impact was evaluated using two metrics:

1. *Availability*: The primary metric of impact is '*stock availability'*, which is the percentage of (immunization session) days on which vaccine stock was available, i.e. did not reach zero-stock.
2. *Responsiveness*: A secondary metric indicating behavior change is replenishment responsiveness after a stock-out event. For this, we measured the '*average response time*' to replenish stock after a stock-out, averaged across all vaccines in all locations.

4.1 Availability

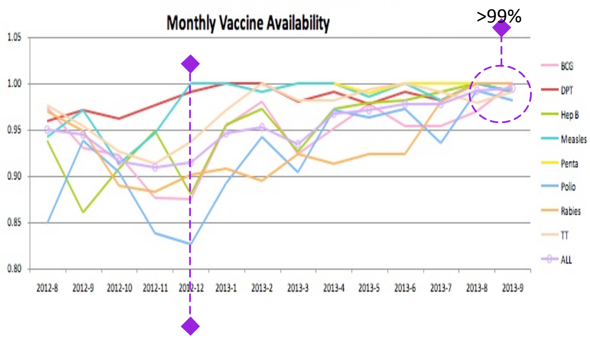

Figure 5. Availability of 9 vaccines

Figure 5 shows a graph of availability on a monthly basis, and presents a compelling picture of impact. The horizontal line at 1.0 represents 100% availability of the vaccines in the correct quantities, where and when they were needed (1.00 = 100%). It is evident that, upon the introduction of the Bulletin Board in December 2012, there has been a steady improvement in availability across *all* vaccines to near *99%*. In addition, we observed a strong reduction in variability across vaccines – by comparing the standard deviation of availability across all vaccines in the first 6 months with the standard deviation in the final 6 months of study. We observed a reduction in variability of 53.51%. This suggests that the software tools and operating procedures have normalized system behavior in a way that availability is roughly similar across all vaccines. Higher variability across vaccines, wherever noticed, was symptomatic of inconsistent ordering or delivery decisions. This represents a strong improvement in supply chain management behavior with the introduction of the Bulletin Board and mobile tools.

This positive change in availability can be attributed to the change in the replenishment behavior of pharmacists at the PHCs, as and when they obtained feedback from supervisors and suppliers upstream in the supply chain. It can be clearly seen that the change in stock management behavior has contributed to increased availability. In addition, suppliers have had early indications on potential stock outs, and thereby facilitated procurement decisions in a timely fashion – be it from the central or alternate supply channels. Visibility of availability and demand across the network also facilitated opportunistic stock re-allocation between PHCs.

4.2 Responsiveness

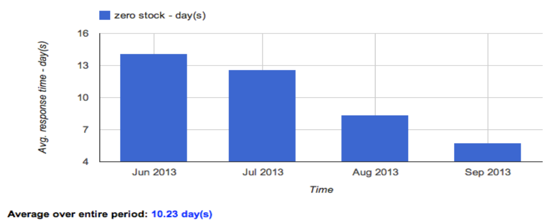

Figure 6. Replenishment responsiveness

Figure 6 shows a chart of monthly average response times to replenish shelves after a stock-out incident. From this chart, we can see that the response time to replenish a stock-out decreased from 14 days to 5 days per vaccine on the average, over a 4-month period – approximately *64%* increase in responsiveness[2].

In summary, it is clear that the Bulletin Board has enabled an increase in replenishment responsiveness, which has resulted in increased availability at the last-mile[3].

4.3 Qualitative improvements

We have seen qualitative improvements across the supply chain, which we gathered through a survey of both pharmacists and supervisors across the PHCs involved in the study. The survey focused on understanding the benefits of the service as perceived by the pharmacists and the supervisors. The results of the survey are summarized below.

[1] Some dips in transaction counts are imminent given the variance in actual consumption patterns across months.

[2] It was important to measure responsiveness after a steady state of behavior was attained within the system, which took roughly 6 months after the introduction of the intervention.

[3] During this period, we ensured that no other interventions were introduced into the supply chain. We focused our effort on changing and evaluating replenishment behavior by the pharmacists, which was independent of supply, and consequently the Bulletin Board became the primary driver of change.

1. As a result of seeing real-time actionable information from lower echelons, district-level supervisors have made more PHC-level visits to examine information that streamed in their Bulletin Board. They have further brought in procedural changes at the PHC-level, wherein the Medical Officer (MO) at the PHC additionally reviews stock availability and mobile data entry by the pharmacist – a significant step in achieving good data quality from the pharmacist.

2. Monthly management review meetings at the district now include "supply chain status and planning" to understand the flow of goods and spot opportunities for re-allocation of stock amongst the PHCs, based on stock visibility across PHCs.

3. Pharmacists were happy to be able to check stock anywhere and anytime, especially at the warehouse, during inventory pickup. The SMS alerts on data entry, stock outs, batch expiry, or similar events, have helped them detect problems in their early stages. Most importantly, the pro-active feedback received from supervisors based on events on the Bulletin Board has significantly helped in resolving stock-outs at the PHC and building stock management capacity. This has inculcated a sense of value and empowerment amongst pharmacists, which has, in turn, strengthened adoption. Pharmacists and health workers are helping each other with data entry and stock management procedures.

4. Due to a habit of weekly or continuous data entry, pharmacists' felt that their mental models of consumption of critical materials have become stronger, resulting in improved ordering.

5. Supervisors are now checking for minimum stock conditions more often to prevent stock-outs, rather than reacting to reported stock-outs with emergency deliveries.

Over the period of 14 months after the Bulletin Board was introduced, we have seen considerable changes in data entry and stock management behavior. In addition, both pharmacists and supervisors feel a sense of value using the tools, and seem to be interacting with one another more frequently to solve problems. We strongly believe that empowering users at all levels is critical to achieving impacts and we need to offer simple tools and procedures, coupled with capacity building to enable positive behavior changes towards better governance.

5. RELATED WORK

There are some instances where the problem of information asymmetry between supply and demand has been addressed using mobile phones. For instance, the problems of providing timely market information (price, in particular) to fishermen, has been addressed in [1], while the problem of providing timely information on weather, best practices and demand indicators to farmers has been addressed in [13]. All these employ SMSes to *push* information to people in the villages. None of these address information asymmetry in the context of optimizing availability of goods in the last-mile, nor do they address the hard problem of collecting reliable transactional data from the last-mile.

Supply chain management using mobile phones has been conventionally applied in urban supply chains using smart phones [7, 17]. There are a few instances of applying information technology in rural supply chains [15, 18]. However, these instances have been either strongly computer-based, SMS-based with limited commodities, restricted to higher-echelons of the supply chain, or use conventional methods of inventory optimization. Neither have we encountered published evidence of reliable transactional data collection from the last-mile, nor any experimental studies demonstrating quantitative improvements in availability.

6. CONCLUSIONS

Evidence suggests that our initial hypothesis was correct – *that people self-organize to improve supply chain performance, if relevant information is made available to them in a timely and consumable fashion*. Stock management behaviors at the last-mile have changed positively and the supply chain has become more responsive to abnormal stock conditions, thereby increasing availability in a significant and sustainable manner.

It is critically important that the *quality* and *timeliness* of information be good to enable effective decision-making and build trust in the system. Our experience shows that an effective *service design* – factoring human, technology, and environmental conditions – is essential to achieve high engagement and data quality. The design should be *user-centric,* accommodating the needs and constraints of users at all echelons. Minimizing the quantum of information needed from the last-mile, personalizing the interface based on user capacity, and crisp operating and review procedures are essential to achieve a sustainable system. With all these in place, we have seen marked behavioral changes with respect to data reporting and stock management over a relatively short period of time.

Ever since the formal study, we have steadily expanded our deployments, and have seen that the above principles have scaled well. At the time of writing, this system and method have scaled to over 400 public health facilities across four states in India, with reasonably high data quality.

We believe this is the first implementation that leverages insights from *information asymmetry theory* and effective *service design* to achieve sustainable supply chain performance in low-resource environments. We have demonstrated through a formal study that this approach does enable sustained change towards better performance.

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