Improving vaccine access: Optimizing storage and hub location in a developing country

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Talk Outline

1. Introduction
   - Systems Modeling Laboratory for Economic Decisions
   - Motivation and statement of need
2. Methodology
   - Supply chain and country profile
   - Model and parameter definitions
   - Data and Data Source
3. Results
   - System improvement: impact on storage capacity
   - Proposed reorganization and outcomes
4. Conclusion
   - Remarks
   - Policy implications

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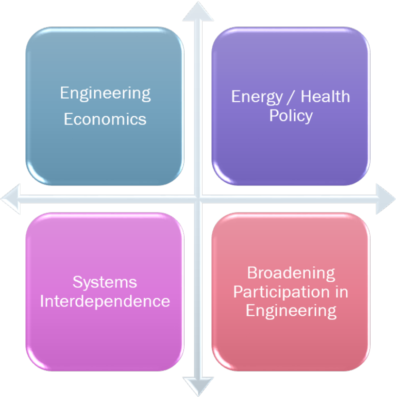
Overview of SysMoLED



- General Algebraic Modeling System (GAMS)
- Visual Basic for Applications in Excel (VBA and Excel)
- MATLAB
- STATA
- Microeconomics

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Current Research

Resilience and Interdependence	• *Deficit evaluation at the nexus of food, energy and water systems* • *Investments to enhance the reliability and resilience of electricity infrastructure systems*	NSF
Technology Management and Policy	• *Synthetic time histories for wind energy in IES* • *Make-or-Buy decision in the wind energy ecosystem*	U.S. DEPARTMENT OF ENERGY
Bio-inspired Self-healing in Power Networks	• *General birth & death processes + chain binomial epidemic models* • *Electrophysiology and inferences from stochastic modeling of biochemical and genetic networks*	NSF
Democratizing Clean Energy Access: CCA	• *Examining community solar programs to understand the factors influencing adoption trends and patterns* • *Evaluating the ecosystem of microgrids in developing countries*	Alfred P. Sloan FOUNDATION
Service Learning for Innovation	• *Service learning projects to improve engineering students' civic engagement and capacity for innovation* • *Improving undergraduate STEM education*	NSF

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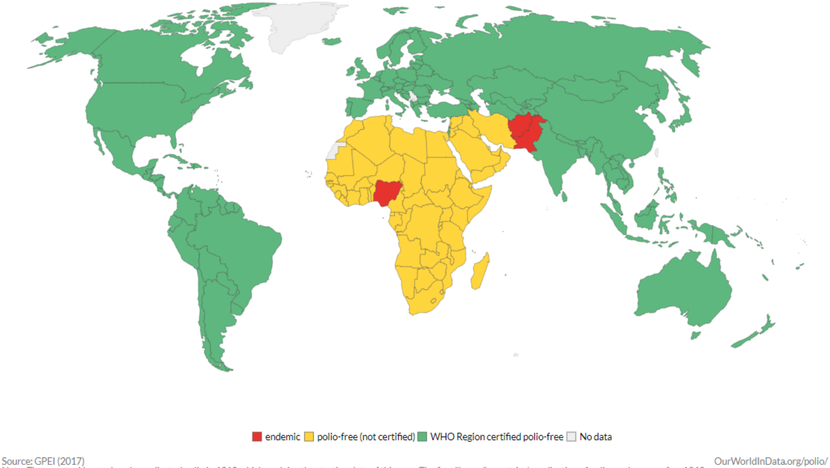
The Scourge of Polio



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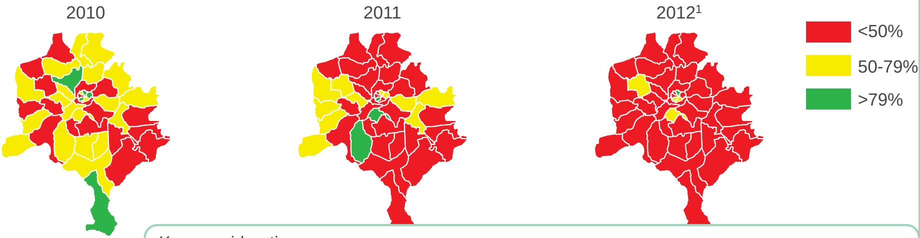
Motivation

- Less than 50% of children had full schedule of basic vaccines
  - Nigeria's overall immunization rate hovers around 70%
  - Country lags in terms of vaccine logistics performance

Routine immunisation (RI) – DPT3 coverage rate by LGAs
%



Key considerations:
Are we bringing in enough vaccines to maximize our coverage?
Is our supply chain strong enough to ensure all facilities are covered with the right frequency?

- There is a significant opportunity for impact and the supply chain plays a major role in this regard

Statement of Need

- Problem of inadequacy inflated by uncertainty in demand
  - Supply chains are strained in many LDCs due to limited infrastructure – placing lives at risk (Kaufmann, Miller, Cheyne, 2011)

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Statement of Need

- Problem of inadequacy inflated by uncertainty in demand
  - Supply chains are strained in many LDCs due to limited infrastructure – placing lives at risk (Kaufmann, Miller, Cheyne, 2011)
- Government-run vaccine supply chains are limited by how to (OPTIMIZE, 2012)
  - maintain vaccine quality throughout the supply chain
  - ensure vaccine availability at service delivery points
  - keep pace with new policies/technology in management

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  - maintain vaccine quality throughout the supply chain
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  - keep pace with new policies/technology in management
- Three themes define supply chain issues in LDCs
  - Structure: central vs. decentralized system
  - Strategy: poor monitoring and reporting
  - Risk: failure of supplies to reach the intended targets

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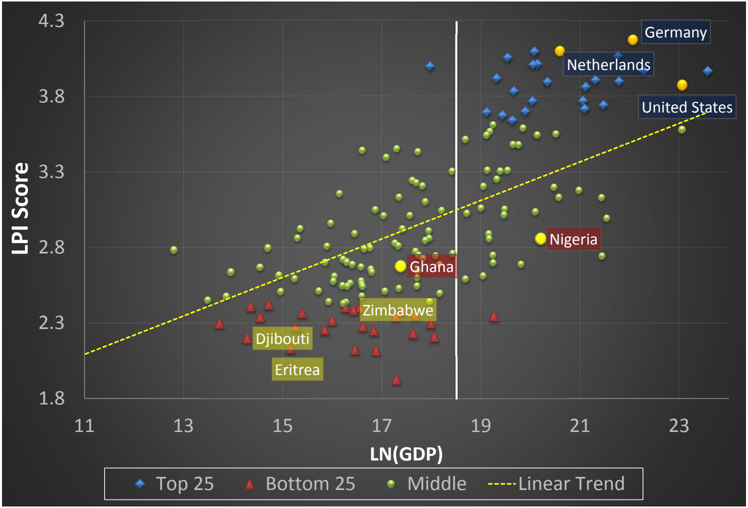
Rationale for Country Choice



LPI from http://lpi.worldbank.org/ and GDP from http://www.imf.org/external/pubs/ft/weo/2014/02/weodata/weoselgr.aspx

- Linear trend represents the correlation between GDP and LPI
  - Bifurcation: top 25 – top right; bottom 25 – bottom left
  - Middle tier with improvement potentials – Ghana, Nigeria

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Approach

- Incorporate uncertainties to estimate vaccine delivery performance
  - ☞ Mismatch or variability in *pushed* quantities as a proxy for demand uncertainty
  - ☞ Shortfalls in delivery due to limitations in cold chain capacities

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Approach

- Incorporate uncertainties to estimate vaccine delivery performance
  - ☞ Mismatch or variability in *pushed* quantities as a proxy for demand uncertainty
  - ☞ Shortfalls in delivery due to limitations in cold chain capacities
- Methodology
  - Developed a model of multi-echelon supply chain network
  - Implemented stochastic optimization in a simulation
  - Introduced supply chain performance metrics

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Country Profile

- Nigeria is the most populated country in Africa (165+ million) with an area of $923,678$ square kilometers ($2\frac{1}{2}\times$ CA)
- Operates a three-tier system of government — Federal, states (36) and Local Government Areas (LGAs, 774 + FCT)

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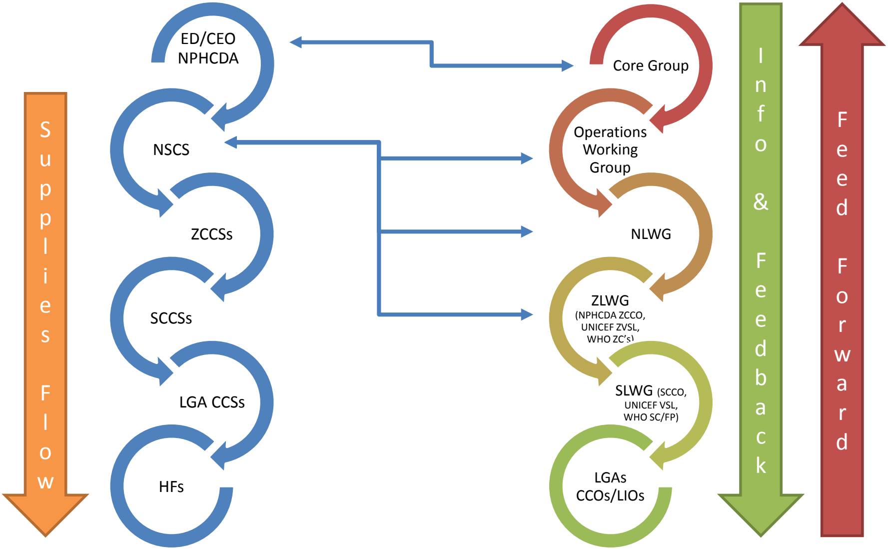
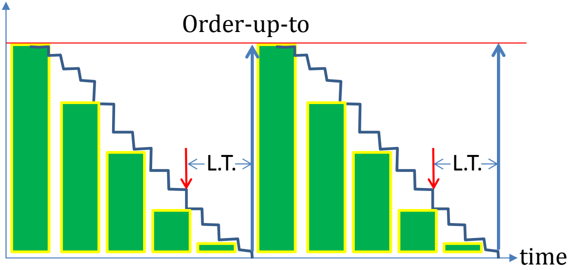
VSL Flow Diagram



Model Characteristics



- Orders from regions to central storage; central storage to manufacturer
- Lead time to receive orders are known
- Demands are independent, log-normally distributed, random quantities
- Back-order are allowed – to be met with the next receipts

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Variable Declaration

- t – time or period
- i – region
- $Q_{i,t}$ – ordered quantity by region i from central storage at time t
- K_t – ordered quantity from the manufacturer at time t by the central storage
- $BIQ_{i,t}$ – beginning inventory for region, i, at time, t
- BIK_t – beginning inventory for the central storage at time, t
- $EIQ_{i,t}$ – ending inventory for region, i, at time, t
- EIK_t – ending inventory for the central storage at time, t
- $sR_{i,t}$ – shipment to region i, at time, t from the central storage
- sC_t – shipment to central storage from the manufacturer at time, t
- P_t – shipments in the pipeline to central storage
- $\widetilde{D_{i,t}}$ is random demand log-normally distributed, $LN \sim (\mu_D, \sigma_D)$

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Parameter Definition

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- $\text{BIQ}_{i,t} = sR_{i,t-1} + EIQ_{i,t-1}$

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- $\mathrm{BIK}_t = BIK_{t-1} - \sum_i sR_{i,t-1} + P_{t-1}$
- $\mathrm{Q}_{i,t} = \begin{cases} \theta_i - (\overbrace{BIQ_{i,t} - \widetilde{D_{i,t}}}^{EIQ_{i,t}}), & \text{if positive} \\ 0, & \text{otherwise} \end{cases}$

– where θ_i is region i's order-up-to quantity, a decision variable

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– where θ_i is region i's order-up-to quantity, a decision variable

- $\text{sR}_{i,t} = \begin{cases} Q_{i,t}, & \text{if} \sum_i Q_{i,t} \leq BIK_t \\ \frac{Q_{i,t}}{\sum_i Q_{i,t}} \times BIK_t, & \text{otherwise} \end{cases}$

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Parameter Definition

- $K_t = \begin{cases} \color{red}{\phi} - \overbrace{(BIK_t + P_t - \sum_i Q_{i,t})}^{EIK_t}, & \text{if positive} \\ 0, & \text{otherwise} \end{cases}$

– where $\color{red}{\phi}$ is the central storage order-up-to quantity, and it is a decision variable

- $EIQ_{i,t} = BIQ_{i,t} - \widetilde{D_{i,t}}$

- $\color{blue}{BOQ_{i,t}} = \begin{cases} \widetilde{D_{i,t}}, & \text{if } BIQ_{i,t} \leq 0 \\ \widetilde{D_{i,t}} - BIQ_{i,t}, & \text{if } 0 < BIQ_{i,t} < \widetilde{D_{i,t}} \\ 0, & \text{otherwise} \end{cases}$

– where $\color{blue}{BOQ_{i,t}}$ is the back-ordered quantity

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Model

- The objective is to minimize the average vaccine inventory in the system while simultaneously meeting requirements

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$$\min_{\theta_i,\phi} \frac{1}{\widehat{T}}\left[\sum_{t=1}^{\widehat{T}}\left(BIK_t + P_t + \sum_{i=1}^{n} BIQ_{i,t}\right)\right]$$

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- $P(Fill\ rate < HIT\%) \leq \delta$

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- $L_{min} \leq \theta_i, \phi \leq U^{max}\ \forall i$

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where

$$[1]\ Fill\ rate = 1 - \sum_{t=1}^{\widehat{T}} \sum_{i=1}^{n} \frac{BOQ_{i,t}}{\widetilde{D_{i,t}}}$$

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$$\min_{\theta_i,\phi} \frac{1}{\widehat{T}} \left[\sum_{t=1}^{\widehat{T}} \left(BIK_t + P_t + \sum_{i=1}^{n} BIQ_{i,t} \right) \right]$$

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$$[1]\ Fill\ rate = 1 - \sum_{t=1}^{\widehat{T}} \sum_{i=1}^{n} \frac{BOQ_{i,t}}{\widetilde{D_{i,t}}}$$

$$[2]\ \delta \in [0.05, 0.20]$$

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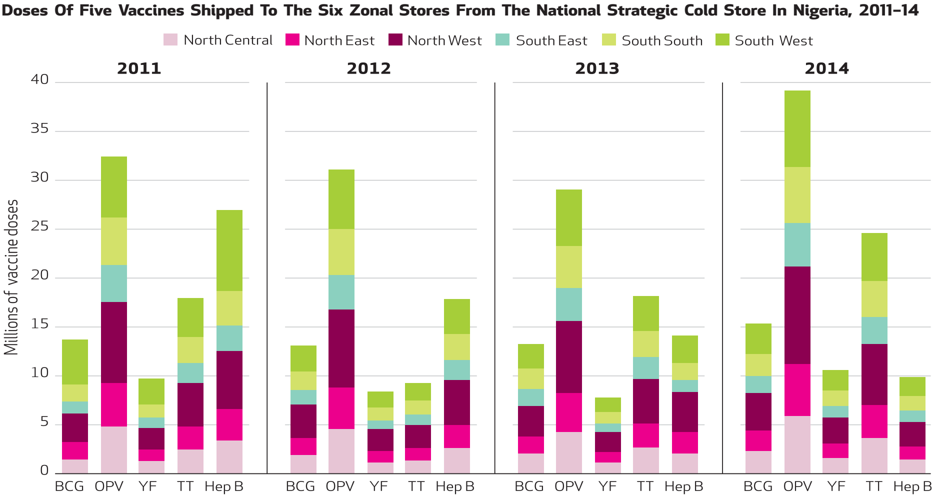
Data: NPHCDA



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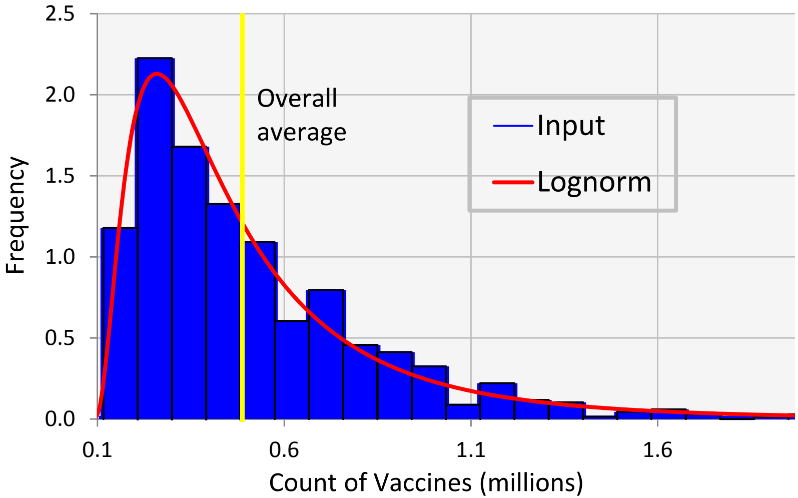
Simulation Properties



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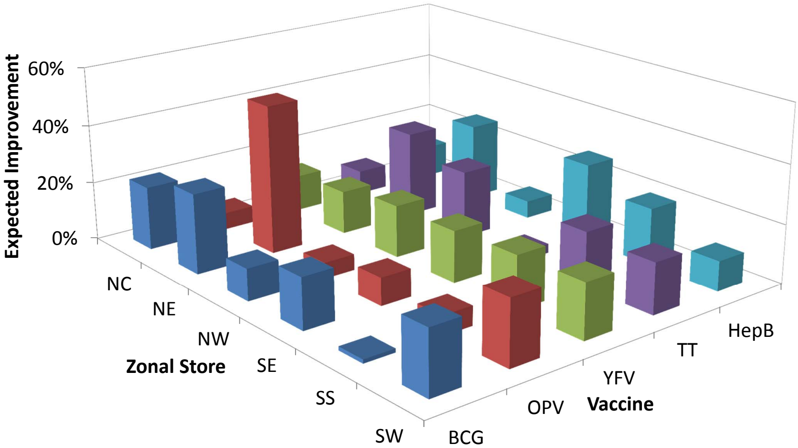
Results: Impact on Storage Capacity



- Polio – NE/SW; YFV all zones: by at least 20%
- Hep B – NE, SS & SE zones: approx. 30%

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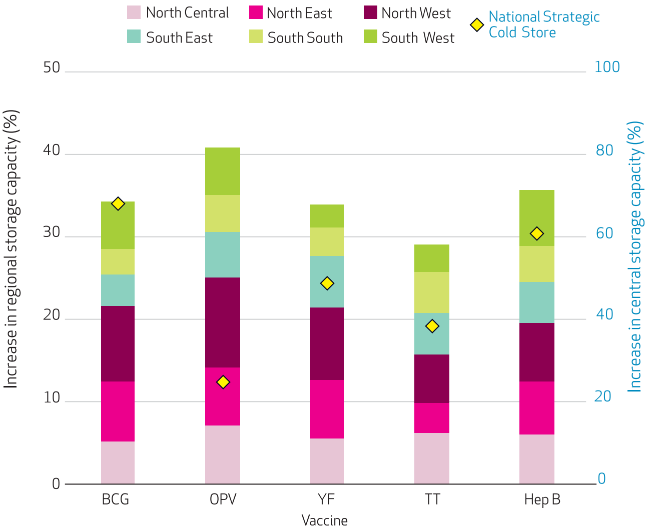
Results with Central Storage

Expected Increase In Vaccine Storage Capacity At Zonal Stores And The National Strategic Cold Store Needed To Improve Reliability To Meet 100 Percent Fill Rate For Five Vaccines In Nigeria



- Highest for BCG & Hep B; OPV least–Polio is not about supplies!

Empirical Implications

Implications

Empirical Implications

- Supply chain performance improvement and uncertainty mitigation require the expansion of existing storage facilities.

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- Not a one-size-fits-all solution: varies by vaccine type and by region.

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- Supply chain performance improvement and uncertainty mitigation require the expansion of existing storage facilities.
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- Problem is exacerbated at the lower echelon of the chain — the last mile!

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Implications

Empirical Implications

- Supply chain performance improvement and uncertainty mitigation require the expansion of existing storage facilities.
- Not a one-size-fits-all solution: varies by vaccine type and by region.
- Problem is exacerbated at the lower echelon of the chain — the last mile!
- Addressing the last mile problems is the key to performance improvement.

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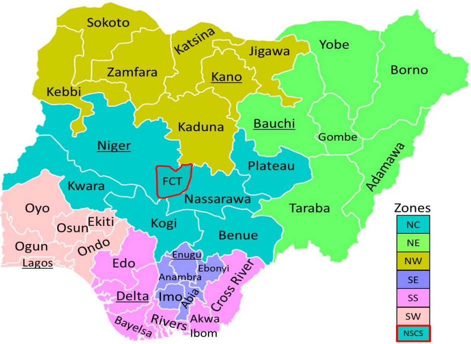
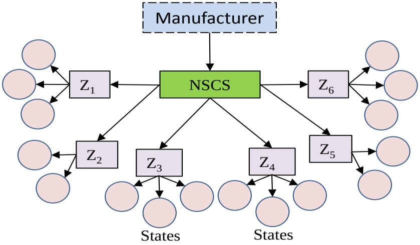
Proposed Reorganization





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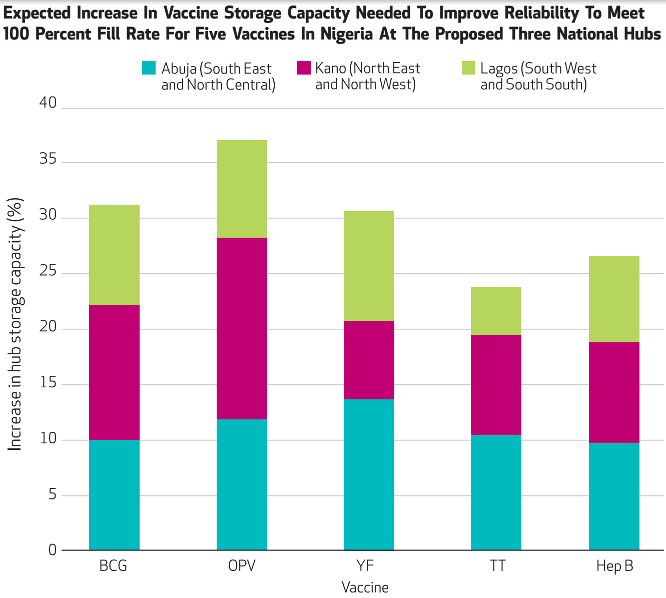
Outcomes



- Hub variances are lower; TT (central) & Hep B (north) need increases!

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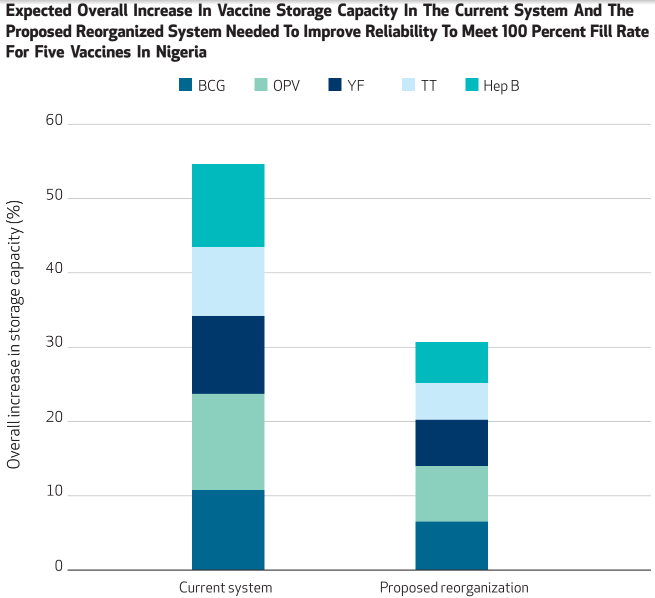
Comparison of Systems



- Capacity increase ≈ 50% lower – TT & YFV require moderate increases!

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Senior Design Team

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journal homepage: www.elsevier.com/locate/vaccine

Evaluating scenarios of locations and capacities for vaccine storage in Nigeria

Check for updates

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ABSTRACT

Many developing countries still face the prevalence of preventable childhood diseases because their vaccine supply chain systems are inadequate by design or structure to meet the needs of their populations. Currently, Nigeria is evaluating options in the redesign of the country's vaccine supply chain. Using Nigeria as a case study, the objective is to evaluate different regional supply chain scenarios to identify

Distance-minimizing Hub Choices

- minimize the distance between the states and the regional hub by choosing the states to use as regional hubs

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$$\min_{P_{i,j},X_i} Z = \sum_i \sum_j D_{i,j} P_{i,j}$$

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Subject to

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Subject to

- $\sum_i P_{i,j} = 1 \qquad \forall j$

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Subject to

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- $\sum_i X_i = NumHubs \qquad (exogenous)$

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- $\sum_i X_i = NumHubs \qquad (exogenous)$
- $\sum_j P_{i,j} \leq X_i \qquad \forall i$
- $\mathrm{X}_{i=FCT} = 1 \qquad (imposed \quad for \quad NSCS \quad scenarios)$

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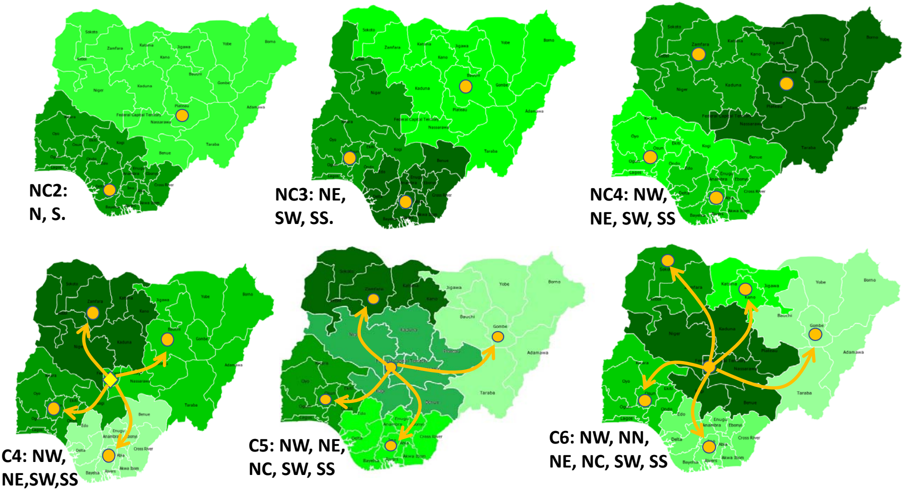
Optimal Hub Locations



Total Cost-minimizing Capacity

- Minimize total system cost

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- Minimize total system cost

$$M = \sum_k \min_{R_{ki}, C_k} \left(W_k + S_k + T_k \right)$$

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Total Cost-minimizing Capacity

- Minimize total system cost

$$M = \sum_k \min_{R_{ki}, C_k} (W_k + S_k + T_k)$$

  - Vaccine cost,
    $W_k = \sum_i \sum_t OQ_{kit} \times \omega_k \quad for \quad k \in (1, 2, \cdots, 5)$

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  - Vaccine storage cost, $S_k = \sum_t BIC_{kt} \times \sigma_{kc} + \sum_i \sum_t BI_{kit} \times \sigma_{kr}$

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Total Cost-minimizing Capacity

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  - Vaccine storage cost, $S_k = \sum_t BIC_{kt} \times \sigma_{kc} + \sum_i \sum_t BI_{kit} \times \sigma_{kr}$
  - Vaccine transportation cost, $T_k = \sum_i [\theta D_i \sum_t H_k AS_{kit}]$

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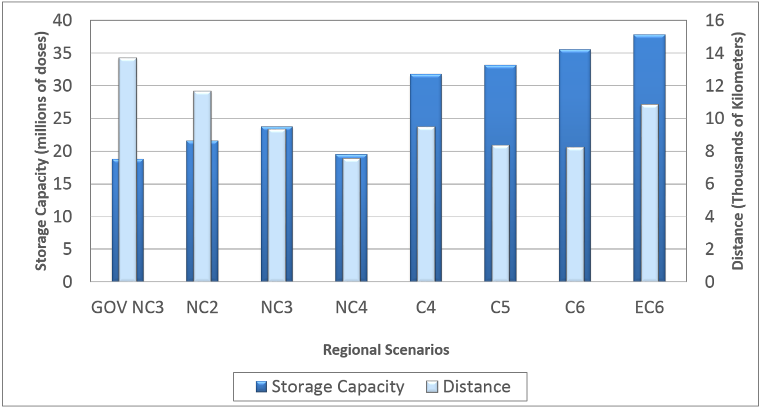
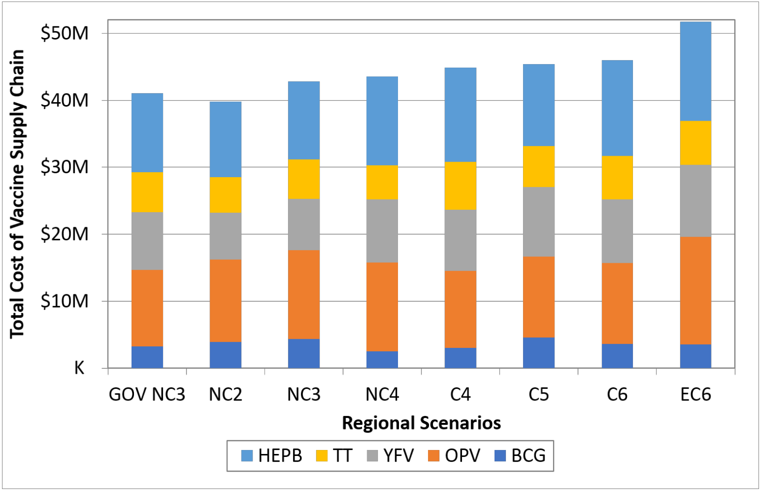
Optimal Distance & Capacity by Configuration



System Cost by Configuration



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Remarks

✓ Problem and approach

- Data-intensive in an environment with hard-to-get data
- Uncertainty in the demand influence the fill rate
- Multi-level supply chain – current/proposed designs
- Minimize vaccines in the system while satisfying performance

✓ Outcomes

- Improved storage infrastructure is required in terms of capacity increases
- Reorganization of existing systems offers performance improvements
- Leverage President's Emergency Plan for AIDS Relief (PEPFAR) in the private sector

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Policy Implications

✍ Improving system performance requires treating each vaccine differently and knowing regional variability

- Immunization policy makers have to consider vaccine availability by vaccine type and by region
- Vaccine for COVID-19 is the first hurdle – getting it to the target population **timely** is another

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  - Immunization policy makers have to consider vaccine availability by vaccine type and by region
  - Vaccine for COVID-19 is the first hurdle – getting it to the target population **timely** is another
- ✍ Reducing the hierarchical complexity of the vaccine supply chain will improve performance
  - Important since the cost of capacity expansion is positively correlated with the scale of expansion
  - Budget-constrained environments: capacity increases to improve performance is feasible even with reduced budgets

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- ✍ Reducing the hierarchical complexity of the vaccine supply chain will improve performance
  - Important since the cost of capacity expansion is positively correlated with the scale of expansion
  - Budget-constrained environments: capacity increases to improve performance is feasible even with reduced budgets
- ✍ Recent success by Nigeria for no newly reported polio case shows efforts must be sustained

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Team

- Roger Miller (LMI)
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Immunization in Kano, Nigeria.
Source: http://www.noi-polls.com/

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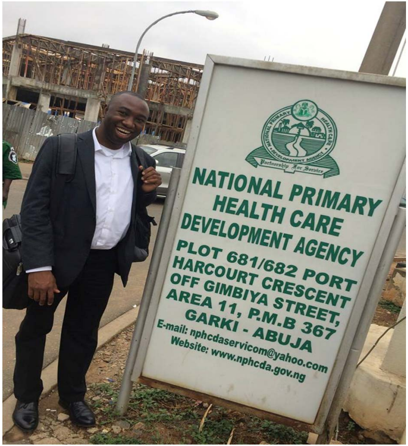

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Random parameters

Model uncertainty parameters.

Vaccine	Estimator	Parameters
OPV	Triangular	min = 0.165; mode = 0.18; max = 0.205
TT	Triangular	min = 0.022883; mode = 0.0593; max = 0.0593
YFV	Point estimate	0.667375
HEP B	Point estimate	0.39
BCG	Beta	a = 0.22039; b = 0.28234; c = 0.057; d = 0.153

Random variables	
φ_{kit}	Random demand for vaccine k in region i at time t
ω_k	Vaccine cost per dose of vaccine k
σ_{ki} and σ_{kc}	Storage cost of vaccine k in region i and the central hub
θ	Transport cost per liter per kilometer

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The Last Mile

- The hurdles at the last mile
  - Specific challenges
- Recommendations
  - Global view of suggested solutions
  - Policy implications

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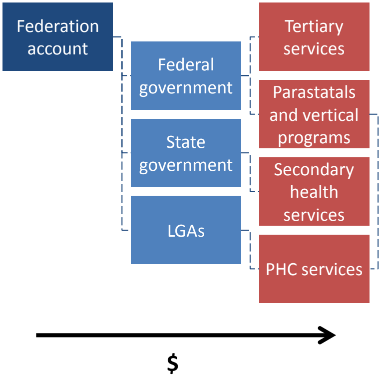
Last Mile Hurdles: Funding $\neq$ Disbursement

Budget structure requires funds to pass through 3 levels to reach RI

Budget flows and reporting structure



Key Implications

Funding flows vary by layer

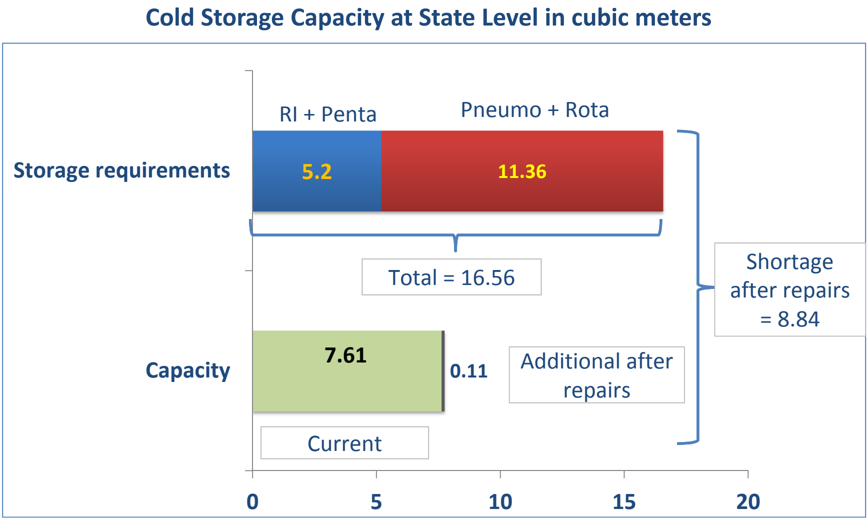
- Federal Government is responsible for funding tertiary care, parastatals and vertical programs
- State Governments fund secondary health services
- Local Government Areas (LGAs) fund Primary Health Care services with additional funding from parastatals and vertical programs

Lack of direct lines of accountability lead to major issues at the state and local level

- States and LGAs often delay, withhold, or shortchange RI funding flows due to lack of political commitment
- Lack of direct lines of authority from supervisor (paid by state government) and supervisee (paid by local government) creates issues in management and promotes lack of accountability

Source: Sabin country profiles http://www.sabin.org/advocacy-education/sustainable-immunization-financing/Nigeria citing Nigeria Health System Assessment 2008, USAID/ Abt. Associates; LARI draft report —desk review JHU & IVAC July 2011

Last Mile Hurdles: Cold Storage Capacity Gaps



- The current state cold storage capacity is inadequate[1]
- An additional WICR is required

[1] Source: Nigeria cold chain capacity assessment in 20 states (2012)

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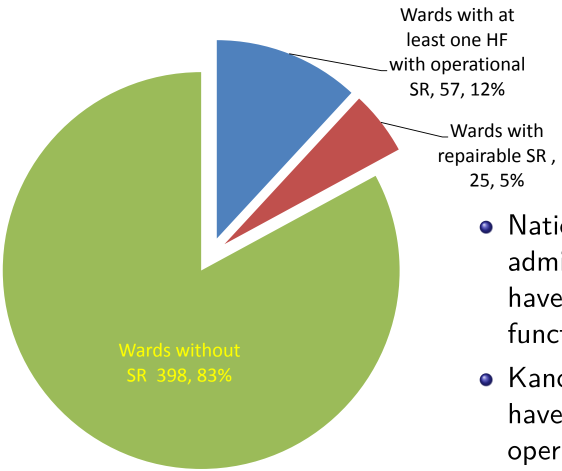
Last Mile Hurdles: LGA Gaps–Solar Refrigerators



- National policy – each administrative ward should have at least 1 HF with functional SR
- Kano – only 12% of wards have at least 1 HF with operational SR
- 5% have repairable SR
- 83% (398) are without SR

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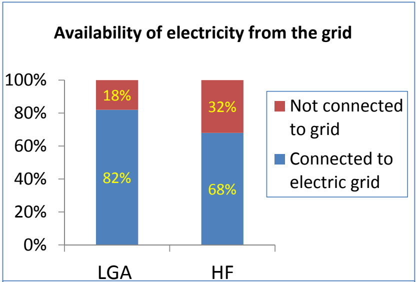
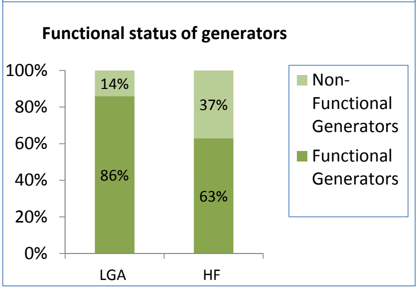
Last Mile Hurdles: Access to Electricity





- Of the 44 LGAs in Kano, 82% (36) are connected to the electric grid.
- 18% (8) of LGAs have no connection to the electric grid
- At the HF level, 68% (67) receive electricity from the grid, while 32% (31) are not connected to the grid

- Kano state cold store does not have its own generator
  - Alternate power supply from Nasarawa specialist hospital and the Polio EOC
- 50 (86%) of the available generators at the LGA level are functional, while 8 (15%) are non-functional
- Of the 60 available generators at the HF level, 38 (63%) are functional, while 22 (37%) are non-functional.

Source:
Nigeria: Cold chain capacity assessment in 20 states (2012)

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Prescriptions/Recommendations

- Improve supply chain visibility
  - Real time data on stocks of immunization commodities.
  - Staff trained on data collection, ensuring high data quality and reporting rates
- Improve procurement and financing practices
  - Streamline funds release; timely & transparent procurement
  - Funds to support distribution; good governance and control of funds
- Improve capacity of staff for cold chain management and immunization commodity handling
- Sufficient cold chain equipment in place to accommodate new and routine vaccines
- Preventative maintenance for cold chain equipment

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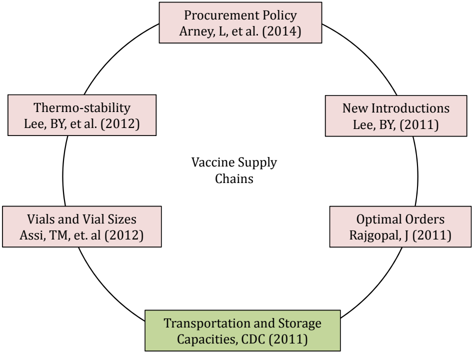
Related Literature



- Validated top-down model is the Highly Extensible Resource for Modeling Event-Driven Supply Chains (HERMES)
  - Uses discrete event simulation of a vaccine supply chain
  - Very broad categorizations
  - Limited to only scenario analysis and not stochastic optimization

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