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Landscaping the structures of GAVI country vaccine supply chains and testing the effects of radical redesign

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ABSTRACT

Background: Many of the world's vaccine supply chains do not adequately provide vaccines, prompting several questions: how are vaccine supply chains currently structured, are these structures closely tailored to individual countries, and should these supply chains be radically redesigned?
Methods: We segmented the 57 GAVI-eligible countries' vaccine supply chains based on their structure/morphology, analyzed whether these segments correlated with differences in country characteristics, and then utilized HERMES to develop a detailed simulation model of three sample countries' supply chains and explore the cost and impact of various alternative structures.
Results: The majority of supply chains (34 of 57) consist of four levels, despite serving a wide diversity of geographical areas and population sizes. These four-level supply chains loosely fall into three clusters [(1) 18 countries relatively more bottom-heavy, i.e., many more storage locations lower in the supply chain, (2) seven with relatively more storage locations in both top and lower levels, and (3) nine comparatively more top-heavy] which do not correlate closely with any of the country characteristics considered. For all three cluster types, our HERMES modeling found that simplified systems (a central location shipping directly to immunization locations with a limited number of Hubs in between) resulted in lower operating costs.
Conclusion: A standard four-tier design template may have been followed for most countries and raises the possibility that simpler and more tailored designs may be warranted.

1. Introduction

Many countries across the world may be outgrowing their current vaccine distribution systems [1–6]. Designed in the 1970s, these vaccine supply chains (i.e., the series of steps, processes, locations, vehicles, and personnel involved in getting vaccines from initial delivery into a country all the way to the people) have long provided life-improving and life-saving vaccines to the world's populations, thus preventing countless disease cases and deaths and saving health care costs and productivity losses [7–16]. However, all innovations eventually require updating. Are the same supply chain designs applicable today or are they outdated with continuing population growth, expanded target populations, and new vaccine introductions (NVIs) to different countries' World Health Organization (WHO) Expanded Program on Immunization (EPI) schedules? Indeed, evidence suggests that supply chain limitations are preventing many mothers and children from getting vaccinated [17–21]. This situation could grow worse throughout this decade, dubbed the "Decade of Vaccines" by Bill and Melinda Gates for an unprecedented number of planned NVIs which have led to development of the Global Vaccine Action Plan (GVAP). Delivery problems also waste significant resources that have been invested in developing and manufacturing vaccines.

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Tackling whether and how to redesign vaccine supply chains requires an understanding of their current structures. Therefore, we first performed a segmentation analysis of the 57 GAVI-eligible countries' vaccine supply chains, profiling and dividing them into logical groups to establish a general taxonomy of GAVI-eligible country vaccine supply chains (Appendix A). We investigated how the observed supply chain morphologies correlate with the countries' characteristics to establish whether there is a rationale for the current supply chain designs. After this segmentation analysis, we chose three sample countries' vaccine supply chains from the largest segment and utilized mathematical and computational modeling to explore how structures and operations could improve through radical redesign (i.e., substantially simplifying the supply chain structure by eliminating all intermediate storage locations except those identified as necessary from a cost standpoint).

2. Methods

2.1. GAVI-eligible countries

The GAVI Alliance is a public–private global health partnership that aims to increase access to vaccines for the world's lowest-income countries. At the time of this study, a country was considered GAVI-eligible if its Gross National Income (GNI) per capita was below or equal to US $1520 [22–24]. Table 1 lists the 57 GAVI-eligible countries and some of their relevant characteristics. We focused on these countries due to their established need for assistance in improving childhood immunization coverage. Our goal was to explore whether these countries simply require support for purchasing vaccines or their immunization systems need improvement.

2.2. Segmenting GAVI-eligible country supply chains by their structure and morphology

We compiled data on each GAVI country and its vaccine supply chain (Appendix A) and segmented the supply chains into clusters based on their structures, characteristics, and morphologies. The first segmentation variable was the number of supply chain levels (i.e., the number of storage locations a vaccine traverses before being administered).

The second segmentation variable was supply chain morphology, determined by calculating the average "branching ratio" for each level. The average branching ratio for a level is the number of locations in the next lower level divided by the number of locations in the current level (e.g., a District level has a branching ratio of ten if, on average, each Store serves ten immunization locations). Calculating branching ratios helped determine how "top-heavy" (i.e., higher branching ratios in the higher levels) or "bottom-heavy" (i.e., higher branching ratios in the lower levels) each supply chain is.

We used Stata, Version 11.2 (Stata Corporation, College Station, Texas) to determine the correlations between various country characteristics (i.e., gross domestic product per capita, under-five mortality, average life expectancy, total land size, expected 2015 surviving birth cohort), average catchment area (i.e., the geographic area divided by the number of immunization locations), average catchment population (i.e., the expected 2015 surviving birth cohort divided by the number of immunization locations), and number of non-immunization supply chain locations (i.e., storage and distribution locations). Because detailed data were available for only a subset of countries' EPI programs, we based cross-country comparisons on the average catchment area and population. It is unlikely that the actual distributions of catchment areas and populations would correlate differently with the supply chain structures.

2.3. Modeling to identify and evaluate potential simplified redesigns of the vaccine supply chain

From the resulting largest GAVI country vaccine supply chain segment, we selected three sample countries to further explore how they could be redesigned and improved. We utilized the HERMES modeling software (Appendix B), developed by our HERMES Logistics Modeling Team, to generate detailed discrete-event simulation models for each country, which served as virtual laboratories for evaluating the current structures and alternative designs using the following steps [17–21]:

- *Simulate the supply chain for 2015:* This involved extrapolating the country's population (based on its expected GAVI cohort) to match projected 2015 population numbers and adding scheduled NVIs to the system. The simulation was run over one virtual year and helped identify future constraints and bottlenecks if no redesign or improvements occur.
- *Perform a "gap analysis":* This analysis determined the additional storage and transport requirements necessary to fulfill demand 100% at all immunization locations without changing the frequency or mode of delivery (i.e., what needs to be added to alleviate bottlenecks).
- *Simulate the supply chain for 2015 after relieving bottlenecks by adding capacity based on the gap analysis:* After the "gap analysis" identified the additional capacity needed, we added the necessary storage devices and transport vehicles to the system (taking into account planned new vaccine introductions), re-ran the simulations, and then tabulated the required capital expenditures and resulting operational costs.
- *Identify an optimized structure for the supply chain:* Our team created a network design optimization model (Appendix B) to identify alternative simplified designs for the vaccine supply chain.
- Perform a "gap analysis" on the simplified/optimized supply chain for 2015
- *Simulate the simplified supply chain for 2015 after relieving bottlenecks by adding capacity based on the gap analysis:* Once the bottlenecks were alleviated, we performed the simulations for the simplified system, tabulating the capital expenditures needed to achieve the system and resulting operating costs. Note that these capital expenditures assume the purchase of new equipment (storage and transport) rather than repurposing of existing equipment from current locations and transport routes which no longer exist in the simplified system.

3. Results

3.1. The structures of GAVI-eligible country vaccine supply chains

As Fig. 1 shows, the number of supply chain levels ranges from three to five. Fig. 2 uses box plots to compare the distribution of some key GAVI country characteristics for the three-level, four-level, and five-level segments. While three-level vaccine supply chain countries tend to be amongst the smallest in both land and population size and five-level countries tend to be amongst the largest, there is considerable overlap. There is also overlap among the three segments in other characteristics such as gross domestic product per capita, average immunization location catchment area and population, under-five mortality, life expectancy, and the Logistics Performance Index (LPI). Measured by the World Bank, the LPI scores factors affecting supply chain logistics in a country, such as the quality of infrastructure.

We further examined the 34 four-level country supply chains (Fig. 3). (Yemen was excluded due to incomplete data.) To study the

Table 1
GAVI-eligible countries' characteristics and new vaccine introduction schedule.

Country name	2011 Population[a] (in millions)	2015 Birth cohort[b] (in millions)	Country area[c] (million km^2)	No. of levels	2010 GDP[d] per capita (GKD)	2010 Life exp[f] at birth, total	Selected planned new vaccine introductions and year			
							MenA	Hib	Rota virus	PCV
Afghanistan	30.1	1.32	0.65	5	1207	48.3			2013	2012
Bangladesh	166.6	3.09	0.13	3	1659	68.6			2012	2014
Benin	9.5	0.34	0.11	4	1587	55.6	2012		2012	2010
Burkina Faso	16.8	0.68	0.27	4	1256	54.9	2010		2016	2011
Burundi	8.7	0.28	0.03	3	409	49.9	2016		2012	2010
Cambodia	15.3	0.29	0.18	4	2194	62.5		2010	2015	2012
Cameroon	20.4	0.69	0.47	4	2294	51.1	2011		2012	2010
Central African Republic	4.6	0.14	0.62	4	789	47.6	2015		2016	2012
Chad	11.8	0.51	1.2	4	1370	49.2	2011		2018	2014
Comoros	0.71	0.03	0.002	4	1096	60.6			2018	2016
Congo, Dem Republic of	69.7	2.82	2.27	5	347	48.1	2014		2013	2011
Côte d'Ivoire	22.1	0.64	0.32	4	1899	54.7	2014		2016	2012
Djibouti	0.89		0.02	3	2308[e]	57.5			2012	2011
Eritrea	5.4	0.20	0.10	3	546	61.0	2016		2015	2013
Ethiopia	87.2	2.49	1.00	4	1041	58.7	2013		2012	2010
Gambia	1.8	0.06	0.01	3	1410	58.2	2013		2011	
Ghana	24.8	0.76	0.23	5	1644	63.8	2012		2011	2011
Guinea	10.6	0.39	0.25	4	1091	53.6	2014		2014	2012
Guinea Bissau	1.7		0.03	3	1186	47.7	2016		2012	2011
Haiti	10.3	0.27	0.03	3	1111	61.8		2011	2020	2019
India	1230.7		2.97	5	3425	65.1		2011	2015	2014
Kenya	41.9	1.53	0.57	4	1651	56.5	2015		2011	2010
Korea, DPR	24.1	0.32	0.12	4	N/A	68.5		2011	2020	2019
Kyrgyz Republic	5.6	0.13	0.19	4	2239	69.4			2012	2018
Lao PDR	6.5	0.14	0.23	4	2551	67.1			2015	2013
Lesotho	2.1		0.03	3	1601	47.4			2014	2012
Liberia	4.2	0.14	0.10	3	419	56.2			2016	2012
Madagascar	20.7	0.74	0.58	4	969	66.5			2013	2011
Malawi	16.1	0.63	0.09	4	882	53.5			2012	2010
Mali	13.6	0.68	1.22	4	1065	51.0	2010		2012	2010
Mauritania	3.4	0.10	1.03	4	2456	58.2	2015		2018	2014
Mozambique	23.9	0.86	0.79	4	942	49.7			2015	2013
Myanmar	51.0	0.78	0.65	4	1950	64.7		2010	2013	2019
Nepal	30.4	0.73	0.14	4	1199	68.4			2014	2012
Nicaragua	5.9		0.12	4	2913	73.7				2010
Niger	16.5	0.77	1.27	4	728	54.3	2010		2018	2014
Nigeria	161.8	5.91	0.91	5	2399	51.4	2011	2010	2016	2011
Pakistan	188.8	4.50	0.77	4	2688	65.2			2014	2011
Papua New Guinea	7.0	0.20	0.45	4	2472	62.4			2015	2012
Rwanda	10.6		0.02	3	1163	55.1	2016		2012	
São Tomé e Príncipe	0.17		0.001	3	1899	64.3			2015	2011
Senegal	13.2	0.43	0.19	4	1935	59.0	2012		2012	2010
Sierra Leone	6.0		0.07	3	827	47.4			2015	2010
Solomon Islands	0.55		0.03	3	2710	67.5			2014	2012
Somalia	9.6	0.38	0.63	4	N/A	50.9			2020	2019
Republic of Sudan	44.1	0.97	1.86	4	2256	61.1	2012		2012	2010
South Sudan	N/A		0.64	4	N/A	61.5	2013			
Tajikistan	7.2	0.19	0.14	4	2163	67.3			2012	2018
Tanzania	46.4	1.85	0.89	4	1434	57.4	2016		2011	2010
East-Timor	N/A		0.01	3	928	62.0		2012	2016	2013
Togo	6.9	0.19	0.05	4	998	56.6	2014		2015	2012
Uganda	35.0	1.51	0.20	4	1272	53.6	2015		2013	2010
Uzbekistan	28.1	0.61	0.43	4	3106	68.0			2012	2018
Viet Nam	90.0	1.54	0.31	5	3205	74.8		2010	2015	2013
Yemen	25.0		0.53	4	2653	65.0			2010	2010
Zambia	13.6	0.54	0.74	4	1562	48.5			2012	2010
Zimbabwe	12.9	0.39	0.39	4	N/A	49.9			2015	2013

[a] Total population in millions, GAVI, 2011.
[b] Birth cohort population in millions for 2015, calculated, GAVI, 2011.
[c] Country land area in million square kilometers, CIA World Factbook, 2012.
[d] Gross Domestic Product (GDP) per capita in Geary–Khamis dollar (GKD), World Bank, 2010.
[e] Gross Domestic Product (GDP) per capita in Geary–Khamis dollar (GKD), World Bank, 2009.
[f] Life expectancy, total, World Bank, 2010.

"morphologies" of this segment, we tabulated the branching ratios at the top level (i.e., between the first and second levels), the middle level (i.e., between the second and third levels) and the bottom level (i.e., between the third level and leaf node level). Morphologies range from those that are relatively bottom-heavy to those which are more top-heavy, falling into three clusters (Fig. 1). The 18 countries in the first cluster have branching ratios that tend to increase as one moves down the supply chain. The seven countries in the second cluster tend to have higher branching ratios at the top and the bottom levels, but lower branching ratios in the middle

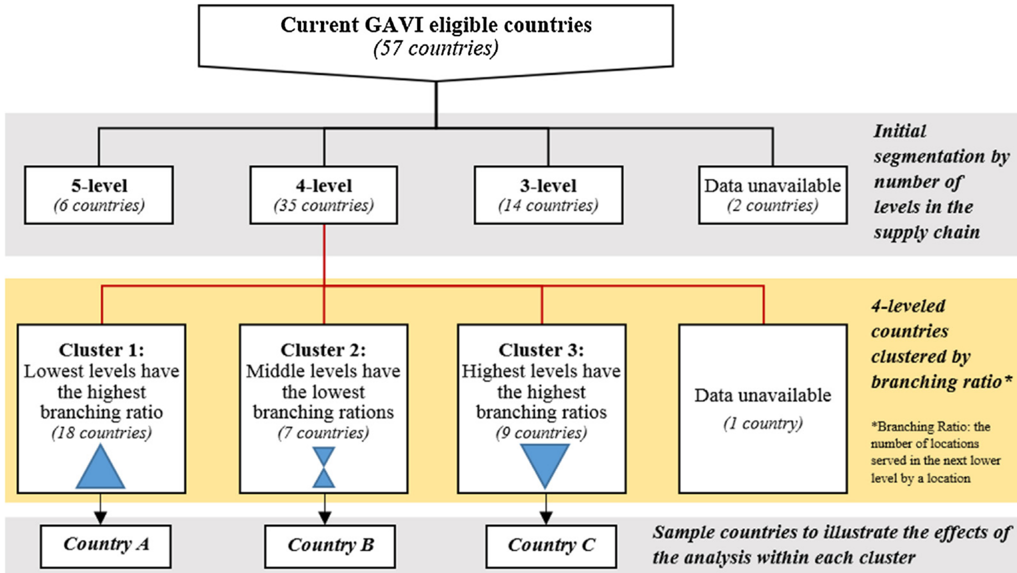

Fig. 1. Segmentation of GAVI-country vaccine supply chains.

between the second and third levels. The nine countries in the third cluster tend to have relatively higher branching ratios at the higher levels.

The average catchment size and catchment birth cohort population for each immunization location are highly variable across the GAVI countries (Table 1). The only indicator that has a significant correlation ($p < 0.01$) with catchment area or catchment population is under-five mortality. Countries with larger catchment areas for their immunization locations tend to have greater under-five mortality (Table 2). The number of non-immunization storage locations in a supply chain is fairly variable across GAVI countries and significantly correlates with only the size of the country's surviving birth cohort. Future analyses may assess correlations with other variables, such as composite EVM scores.

3.2. Sample Country A

Country A has a four-level vaccine supply chain that falls into Cluster 1 and in 2011, provided a vaccine availability of 90%. Our baseline runs suggest that in 2015, with rotavirus and pneumococcal vaccines added to the WHO EPI, Country A's vaccine supply chain will experience transport bottlenecks between all levels (most egregious between the District Stores and immunization locations) and storage bottlenecks at all levels, dropping vaccine availability to 25% and resulting in a logistics costs per dose administered of $0.54 (Table 3).

As Table 3 shows, simply adding both transport and storage capacity (two new large cold rooms at the Central level, four large cold rooms and buildings to house them at the Regional level, 29 (216 L) net refrigerators at the District level, 327 (76 L) net refrigerators at the immunization locations, and enough cold boxes to fill the 94 new trucks) could alleviate these bottlenecks, improve the vaccine availability to ∼100%, decrease the logistics cost per dose administered to $0.28, and entail a total capital expenditure of about $6.7 million USD.

As Table 3 delineates, changing the bottom level transport from motorcycles that travel from one immunization location to one District Store to trucks that make loops from one District Store to four immunization locations could drop the logistics cost per dose administered even further. We assumed four immunization locations per loop because this represents a workload that can be completed in one day. The annual operating costs are higher in this scenario, but the logistics cost per dose is lower because more patients can be served.

The network optimization model identified two potential structures, each with one Central Store and merging the current Regional and District sites into (1) seven Regional Hubs, and (2) 14 Regional Hubs. Table 3 shows the capital expenditure required to achieve this structure and the resulting operating costs. The limitation of the seven-Hub structure is that a number of longer trips would result, with 15% of the routes requiring two days. However, the 14-Hub structure would reduce the number of trips to 4% of the routes requiring over two days and maintain the same logistics cost per dose as the seven-Hub structure but require a higher capital expenditure (Table 3). Note that all of these capital expenditures could significantly decrease if existing storage and transport

Table 2
Correlation analysis of indicators.

	Average catchment area (km^2/no. of immunization locations)	Average catchment population (GAVI surviving cohort/no. of immunization locations)	Non-immunization sites
GDP	0.083	0.149	0.128
Under-five mortality	***0.465******	−0.113	−0.098
Life expectancy	−0.242	0.192	0.213
Land size	–	0.058	0.206
GAVI surviving birth cohort	0.078	–	***0.461******
Catchment area	–	–	−0.145
Catchment population	–	–	0.005

[*] Indicates significant correlation ($p < 0.01$).

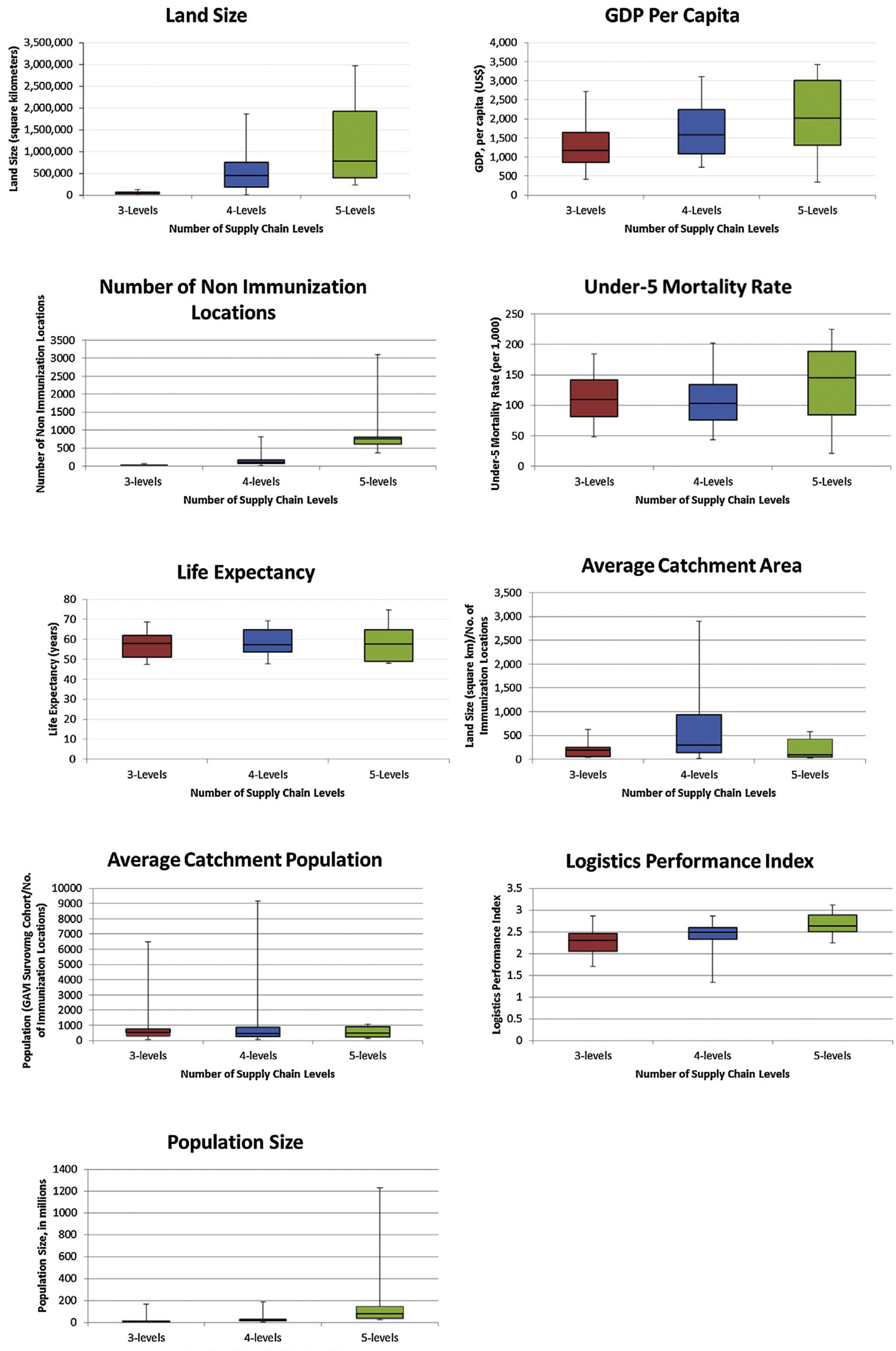

Fig. 2. Comparison of characteristics for three-level, four-level and five-level countries.

equipment from current locations that would no longer be required in a simplified system could be repurposed.

3.3. Sample Country B

Country B also has a four-level vaccine supply chain. Our baseline runs suggest that in 2011, without pneumococcal vaccines, the logistics cost per dose would be $0.46. If no storage or transport is added, by 2015 (with pneumococcal vaccine added to the WHO EPI) Country B's vaccine supply chain will experience transport bottlenecks at all levels, particularly at the top level where there are currently no cold trucks, and storage bottlenecks at the Central and Regional levels, plummeting vaccine availability to 29%. Prior to any fix, the 2015 logistics cost per dose would be $0.65

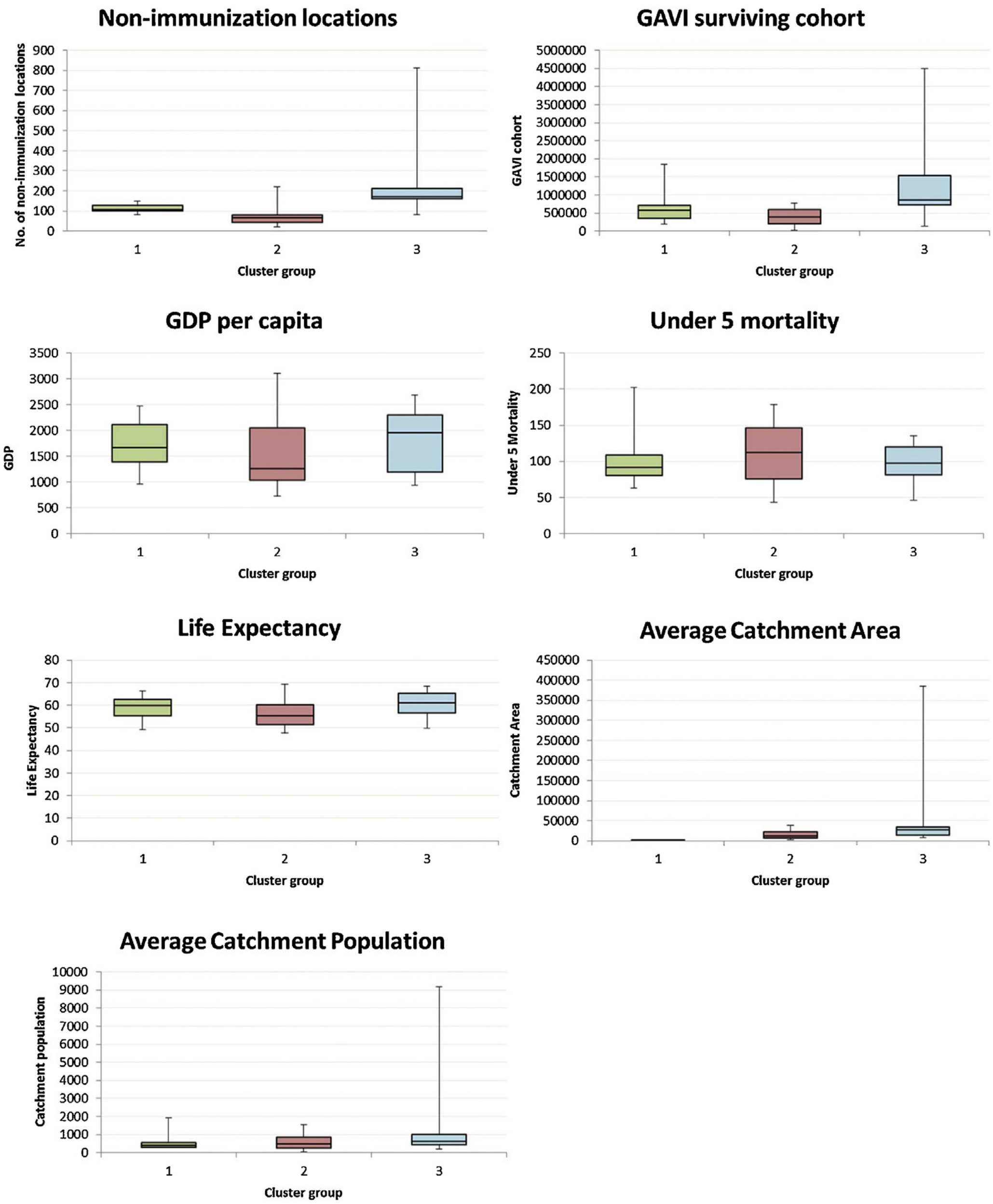

Fig. 3. Clusters for four-level supply chains.

(Table 3). Table 3 shows how adding transport loops (i.e., 4 × 4 trucks instead of motorcycles and allowing these trucks to deliver to four Health Centers per trip) and needed transport capacity to this fix could lead to some additional gains similar to those seen in Country A.

The network optimization model identified three potential simplified structures for Country B, each with one Central store and merging the current Regional and functional District sites into (1) seven Regional Hubs, (2) 14 Regional Hubs and (3) 28 Regional Hubs. Table 3 shows the capital expenditures required to achieve each of these structures and the resulting operating costs. The limitation of the seven-Hub structure is that a number of long trips would result; about 23% of the routes would be over 3 days. Doubling the number of Hubs would decrease the number of routes over three days to about 11%. When 28-Hubs are used, the number of routes exceeding three days decreases to about 5%. Again, reassigning existing transport and storage equipment could substantially reduce capital expenditures.

3.4. *Sample Country C*

Country C has a four-level vaccine supply chain that falls into Cluster 3. Our baseline runs suggest prior to any fix, the logistics cost per dose at baseline in 2015 would be $1.17. Alleviating bottlenecks to get coverage up to ∼100% would necessitate the addition of seven cold rooms and one truck at the Central Store; three cold rooms, four refrigerated trucks, and two trucks at the Regional level; 183 refrigerators (216–105 L) and five trucks at the District level; and 909 (75–99 L) net refrigerators at the immunization locations; entailing a total capital expenditure of $2.4 million (Table 3). This figure is lower than all the scenarios in Countries A and B because Country C is already using trucks and looped routes to serve the lowest level in the supply chain. The resulting annual logistics cost per dose administered would be $0.60 less than the 2015 baseline logistics cost per dose (Table 3).

The network optimization model identified two potential simplified structures, each with one Central store and consolidating

Table 3
Logistics cost per dose administered and costs for current vs. simplified vaccine supply chain structure and capital expenditures required for three sample countries.

Scenario	Vaccine availability (%)	Logistics cost per dose administered	Annual operating costs (USD)					Capital expenditures (million USD)				Total investment cost per birth (USD)
			Labor costs	Storage costs	Transport costs	Building costs	Total	Transport	Storage	Building	Total	
Country A												
2015 Baseline	25	$0.54	$454,336	$772,145	$551,582	$60,757	$1,838,820	n/a	n/a	n/a	n/a	n/a
Baseline + cold capacity, trucks, and transport loops	100	$0.20	$454,336	$1061,758	$812,678	$85,129	$2,413,901	$4.63	$1.64	$0.45	$6.72	$8.77
Simplified: 7-Hubs	100	$0.15	$352,203	$892,224	$614,659	$59,338	$1,918,424	$1.28	$1.44	$0.75	$3.48	$4.53
Simplified: 14-Hubs	100	$0.15	$352,203	$953,256	$597,761	$99,137	$2,002,357	$1.72	$1.68	$1.35	$4.69	$6.20
Country B												
2015 Baseline	29	$0.65	$449,652	$724,593	$289,719	$157,110	$1,621,074	n/a	n/a	n/a	n/a	n/a
Baseline + cold capacity, trucks, and transport loops	100	$0.26	$449,652	$887,093	$348,364	$166,884	$1,851,993	$2.55	$0.84	$0.30	$3.69	$7.25
Simplified: 7-Hubs	100	$0.23	$295,611	$648,138	$650,237	$46,120	$1,640,106	$0.91	$0.31	$0.30	$1.52	$2.99
Simplified: 14-Hubs	100	$0.23	$295,611	$664,142	$639,008	$72,692	$1,671,453	$0.99	$0.31	$0.30	$1.61	$3.15
Simplified: 28-Hubs	100	$0.21	$295,611	$691,351	$415,958	$135,610	$1,538,530	$1.16	$0.36	$0.30	$1.82	$3.58
Country C												
2015 Baseline	43	$1.17	$9290,383	$1643,967	$615,952	$280,251	$11,830,553	n/a	n/a	n/a	n/a	n/a
Baseline + cold capacity	100	$0.57	$9290,383	$2417,763	$1058,808	$311,238	$13,078,192	$0.90	$1.02	$0.51	$2.43	$1.58
Simplified: 12-Hubs	100	$0.53	$8406,878	$2094,552	$1513,351	$101,230	$12,116,011	$4.41	$0.92	$0.25	$5.59	$3.65
Simplified: 25-Hubs	100	$0.53	$8406,878	$2154,060	$1278,651	$175,709	$12,015,298	$5.04	$1.16	$0.25	$6.46	$4.22

Regional and District stores into (1) 12 Regional Hubs and (2) 25 Regional Hubs with the required capital expenditures and resulting operating costs seen in Table 3. Once again, reassigning existing transport and storage equipment could substantially reduce these expected capital expenditures.

The drawback of the 12-Hub structure is that 30% of the trips would be two or more days, compared to 16% of the trips in the 25-Hub structure. Only 1% of the trips in the 25-Hub case would be three or more days in duration.

4. Discussion

The vast majority of GAVI-eligible countries have vaccine supply chains that consist of four levels, despite their wide diversity of geographical areas, population sizes, and other characteristics. The only exceptions are a few particularly large countries with five-level vaccine supply chains (India and the Democratic People's Republic of the Congo, among others) and a small group of smaller countries that have three-level supply chains (Burundi, Djibouti, Gambia, São Tomé e Príncipe, and East Timor, among others). This striking consistency among GAVI-eligible countries suggests that a standard four-tier design template may have been followed for most countries. When a standard format is being followed, one must wonder whether a more tailored approach is warranted. Indeed, our analyses of three sample countries suggest that there may be an excess of storage locations and transport routes in many vaccine supply chains.

Our modeling suggests that simplified systems may provide substantial cost savings for countries in the largest (i.e., four-level) GAVI vaccine supply chain segment. For two of the sample countries, the simplified system accrued not only lower operating costs but also lower capital expenditures than maintaining the current system structure and relieving the bottlenecks. The third required higher capital expenditures but resulted in lower operating costs. While other countries in this four-level segment may vary, these findings that simplified systems may be favorable are encouraging. Future work can explore these solutions in the other GAVI four-level (and three- and five-level) supply chain countries.

There are advantages to having more levels and storage locations in a supply chain. Adding levels essentially decentralizes operations, spreading responsibility and risk throughout more locations and improving response time. For example, having more levels may allow a supply chain to respond faster to unexpected events because distribution centers are closer to the immunization locations. Having more storage locations and transport routes can reduce vulnerability to events such as power outages, fire, theft, personnel loss, and vehicle breakdowns. Having more levels also reduces the distance each vehicle travels.

However, these advantages may not outweigh the disadvantages. Having too many levels complicates coordination, increases the number of sites to manage, reduces economies of scale, and introduces redundancies. Additional levels also contribute to increased time spent in storage, raising the risk of wastage due to temperature exposure or expiry. As a result, many commercial supply chains opt for fewer levels (e.g., automotive distribution traditionally has three levels: the manufacturing site where cars are built, intermediate distribution points, and dealerships, analogous to the Central Store, Hub, and immunization locations, respectively) [27].

In improving supply chains, operations costs may not be the only factor to consider. The choice of storage locations often results from political considerations (e.g., Districts with more political clout may have more locations or locations may be placed in highly visible areas for visitors). Storage locations may also serve multiple purposes (e.g., storing other medical products, food, and durable goods) and gainfully employ people who may otherwise be unemployed. Access to skilled labor, local weather, and road conditions may also play key roles.

Additionally, various redesign options may be more or less desirable depending on funding sources. For example, a stakeholder who is responsible for funding capital costs but not operating costs may prefer system changes that incur lower capital expenditures rather than selecting a design with lower operating costs. Or if a country has recently invested in expanding cold chain capacity, stakeholders may not prioritize redesign until the new equipment is nearing the end of its useful lifetime. Preparing a redesign plan for a country and generating buy-in may also require substantial time and financial investments.

The potential solutions we suggest for these sample countries are approximate rather than precise. The best system for every country may not be a seven-Hub or 14-Hub system, but could actually be a 10-Hub, 12-Hub, etc. system. For example, population density influences the number of optimal Hubs, as more densely populated areas required more Hubs in the sample countries. Countries may also differ in the number of locations that can be visited in a single day, as our assumption of four may not be feasible where locations are separated by long distances or difficult terrain.

This analysis arose when the GAVI supply chain strategy was being formulated and helped provide information to the Bill and Melinda Gates Foundation (BMGF), UNICEF, WHO, and GAVI. This study intends to serve as an initial exploration to further the discussion on whether vaccine supply chains ought to be simplified in order to meet the GAVI Supply Chain Strategy goal of strengthening health systems to improve effectiveness and efficiency in vaccine supply chains [28]. Subsequent work can incorporate more data and information from countries to move toward more precise and implementable solutions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.vaccine.2015.07.033

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