

Balancing Open-Vial Wastage and Timeliness in Outreach Immunisation: A Multiple-Choice Knapsack Model for Session-Frequency Planning in a Tribal District of India

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Abstract— Background. In India's Universal Immunization Programme, most rural children are vaccinated at village outreach sessions held by auxiliary nurse midwives. BCG, measles-rubella (MR) and rotavirus (RVV) vaccines are excluded from the open vial policy, so any doses left in an opened vial are discarded after the session. How often each village receives a session therefore determines both how long a due child waits and how much vaccine is wasted. The national microplanning rule sets this frequency from the monthly injection load, without considering wastage.

Methods. We formulate the district-wide choice of session frequency as a multiple-choice knapsack problem, a mixed-integer linear program that minimises the expected annual cost of non-OVP doses opened plus per-session operating costs. The constraints are taluka-level workload budgets and a ceiling on the dose-weighted mean waiting time. Expected open-vial wastage is computed exactly under Poisson attendance, and we prove it cannot fall when a village's sessions are split more finely. The cost-timeliness Pareto frontier is traced with the ϵ -constraint method. The model is applied to all 930 inhabited villages of Nandurbar district, Maharashtra. Inputs come entirely from public sources: Census 2011, IIPS district population projections, the state's rural vital statistics for 2021, NFHS-5, Ministry of Health and Family Welfare norms and UNICEF contract prices.

Results. The ministry's rule implies 885 sessions a month, a 15.66-day mean wait and an expected cost of INR 1.327 crore a year. Holding the waiting time and each taluka's workload at those levels, the optimal plan costs 4.3% less (INR 5.64 lakh a year) and needs 76 fewer sessions a month. If BCG and MR may be offered at a subset of sessions, the saving rises to 7.6% (INR 10.12 lakh), with 13,614 fewer doses opened each year, although MR then waits longer. Monte Carlo simulation

confirms the analytical costs to within 0.02%. The savings persist under every sensitivity scenario tested and under over-dispersed attendance; with 10-dose MR vials they reach 6.3% (all vaccines at every session) and 16.6% (BCG/MR at a subset). The linear-programming relaxation is within 0.005% of the integer optimum, and each instance solves in seconds with free software.

Conclusions. Setting session frequency by village size and vaccine wastage, rather than injection load alone, reduces cost without lengthening waits or adding workload. The model can be run by district immunisation officers from routinely available data.

Index Terms— routine immunisation; open vial wastage; session frequency; multiple-choice knapsack problem; mixed-integer programming; ϵ -constraint method; vaccine cold chain; India

I. INTRODUCTION

India's Universal Immunization Programme (UIP) targets about 2.67 crore (26.7 million) newborns and 2.9 crore pregnant women each year, making it one of the largest public vaccination programmes in the world (PIB, 2024). In rural India most childhood doses are not given at health facilities but at outreach sessions. An auxiliary nurse midwife (ANM) posted at a sub-centre collects vaccines from the primary health centre (PHC) in an insulated carrier, vaccinates the children an accredited social health activist (ASHA) has mobilised in a village, and returns the unused stock the same day. How often each village receives such a session is fixed once a year in the sub-centre microplan, following a rule set out in the Ministry of Health and Family Welfare's Immunization Handbook

for Health Workers (MoHFW, 2018). Villages with fewer than 1,000 residents receive a session every quarter; larger villages receive one every second month, monthly or twice a month, depending on their monthly injection load.

The frequency decision creates a trade-off that the rule does not address. Under the open vial policy, opened vials of OPV, pentavalent, PCV, IPV, DPT, TT and hepatitis B vaccines may be reused at later sessions for up to 28 days. BCG, measles–rubella (MR) and rotavirus vaccine (RVV) are excluded and must be discarded within four hours of opening (MoHFW, 2018; MoHFW, 2019b). A session attended by one child due for MR therefore consumes a whole five-dose vial. More frequent sessions shorten the time a child who has become due must wait, but they divide the same children across more sessions, so fewer doses are used per vial. The National Vaccine Wastage Assessment found service-level wastage of 56.8% for BCG, 40.9% for RVV and 31.5% for measles-containing vaccine, against 4.8% for pentavalent and 0.2% for PCV (MoHFW, 2019a). Session frequency also consumes resources directly: every session requires ANM time, an ASHA mobilisation incentive of INR 150 (NHM, 2024) and an alternate vaccine delivery (AVD) payment of INR 90 to INR 450 depending on terrain (MoHFW, 2019c).

The trade-off is sharpest in districts made up of many small, dispersed villages. Nandurbar district, in the Satpuda hills of north-western Maharashtra, is 83.3% rural and 69.3% Scheduled Tribe. Its median village had between 921 and 1,532 residents in 2011, depending on the taluka (Census of India, 2011). Full immunisation among children aged 12–23 months rose from 32.8% in NFHS-4 to 72.4% in NFHS-5, but remains well short of the national goal of 90% (IIPS, 2021). Under the ministry's rule, 273 of its 930 villages qualify only for quarterly sessions.

This paper addresses three research questions:

1. For a given level of timeliness and workload, what combination of village session frequencies minimises the expected annual cost of wasted non-OVP vaccine and session operations, and how does it compare with the ministry's microplanning rule?
2. How does the minimum cost rise as timeliness improves, and at what point does ANM

workload, rather than cost, become the binding limit?

3. How much additional saving is available if the wastage-prone vaccines (BCG and MR) are offered at only a subset of sessions, and what does this cost in timeliness for those vaccines?

The paper makes four contributions. First, it formulates village-level session frequency, the decision a district immunisation officer actually controls, as a multiple-choice knapsack problem (MCKP) with taluka workload budgets and an access constraint. Second, it derives expected open-vial wastage exactly under Poisson attendance and proves that splitting a village's sessions more finely can never reduce it. This gives a formal basis for a pattern that empirical studies have repeatedly observed. Third, it traces the full cost–timeliness Pareto frontier with the ϵ -constraint method, showing where additional sessions become expensive and where ANM capacity binds. Fourth, it applies the model to all 930 inhabited villages of a tribal district using only public data and national norms, validates it by Monte Carlo simulation, and compares it directly with the plan produced by the ministry's rule.

Section 2 reviews the literature. Section 3 describes the study setting and data. Section 4 presents the model and solution method, and Section 5 the results. Section 6 discusses implications and limitations, and Section 7 concludes.

II. LITERATURE REVIEW

This section reviews five bodies of work that bear on the session-frequency decision: operations research (OR) on vaccine supply chains in general; network design and simulation for routine immunization in low- and middle-income countries (LMICs); open-vial wastage, vial size and vial-opening policy; the planning of outreach and vaccination sessions; and studies of India's immunization programmed. It closes by positioning the present study against them.

2.1 Operations research in vaccine supply chains

Interest in vaccine logistics within OR has grown rapidly. Duijzer et al. (2018) survey the field and observe that publications usually address one logistical aspect in isolation; they propose a broader framework so that open research questions can be identified and contributions are not overlooked. Lemmens et al. (2016) review integrated supply chain

network design models and set out the key issues that distinguish vaccine supply chains from other supply chains. Two commentaries in *Vaccine* argue that supply chain design shapes how much benefit a vaccine delivers. Lee and Haidari (2017) show how supply chain constraints affect decisions from preclinical design through to funding. Rao et al. (2017) describe how immunisation supply chains are being redesigned as new vaccines are introduced. The COVID-19 pandemic added a large new literature, reviewed by Dey et al. (2024), which spans site selection, inventory, allocation, distribution and routing, frequently coupled to epidemiological models.

2.2 Network design and simulation for routine immunisation

For routine immunisation in LMICs, the foundational optimisation model is that of Chen et al. (2014). They formulate a linear programme of the WHO Expanded Programme on Immunization (EPI) distribution network that maximises the number of fully immunised children, subject to cold-storage and transport capacity at each tier, and adapt it to Niger, Thailand and Vietnam. Later work turns from planning flows through an existing network to redesigning the network. Lim et al. (2022) develop a mixed-integer programme that locates intermediate distribution centres, selects flow paths, allocates vehicles and chooses cold-storage devices, without requiring the traditional four-tier structure. They solve larger instances with a hybrid heuristic-MIP method using data from sub-Saharan Africa. Yang et al. (2021) propose an algorithm for network design problems too large for commercial MIP solvers. Azadi et al. (2024) add demand uncertainty through chance-constrained programming. Their Niger case shows that removing the regional tier and moving cold storage to clinics raises coverage, and that heat-stable formulations of bulky vaccines free cold-chain space. In India, Sripada et al. (2023) build multi-period models that minimise inventory, ordering, transport, personnel and shortage costs across a multi-tier cold chain, illustrated with COVID-19 vaccines in Bihar.

A parallel stream uses discrete-event simulation, principally the HERMES platform. For Niger, these studies examine changing the measles vial size (Assi et al., 2011), removing the regional level (Assi et al., 2013), adding transport rather than storage capacity

(Haidari et al., 2013) and making individual vaccines thermostable (Lee et al., 2012). Redesigns of Benin's chain (Brown et al., 2014) and Mozambique's (Lee et al., 2016) raised vaccine availability while lowering logistics cost per dose. In Mozambique, availability in Gaza province rose from 66% to 93% and cost per dose fell from US\$0.53 to US\$0.32. These simulations capture detail that optimization models abstract away, but they evaluate a small set of pre-specified scenarios rather than searching for the best design.

2.3 Open-vial wastage, vial size and vial-opening policy

Open-vial wastage arises because a multi-dose vial of a vaccine that cannot be kept once opened must be discarded after the session, however few doses were used. India's open vial policy allows opened vials of qualifying vaccines to be reused at later sessions for up to 28 days, but BCG, MR, RVV and JE vaccines are excluded (MoHFW, 2018). Empirical studies consistently find high wastage for the excluded vaccines. In Bangladesh, Guichard et al. (2010) measured average wastage of 84.9% for BCG and 69.7% for measles, mainly from opened vials at outreach sites. Across 19 Gavi-eligible countries, Parmar et al. (2010) found that median wastage rose from 5% for single-dose vials to 10% for 10-dose vials, with the range widening from 1–10% to 4–44%. In Ghana, Mozambique and Pakistan, Mvundura et al. (2023) found open-vial wastage of 0.08–3% for single-dose vials and multi-dose vials that can be kept for four weeks, but 5–33% for multi-dose vials discarded within six hours, highest for measles-containing vaccine. They also reported that such vaccines were sometimes offered less often than others, creating missed opportunities for vaccination. For India, the National Vaccine Wastage Assessment (MoHFW, 2019a) reported the service-level rates quoted in Section 1 and concluded that vaccines presented in 10 or more doses per vial have higher wastage even where the open vial policy applies. Das et al. (2020) documented two years of wastage in Kangra (Himachal Pradesh) and Pune (Maharashtra). BCG wastage was 37.1% and 35.1% respectively, and MR wastage in Kangra was 40.5%. Moving rotavirus vaccine from 5-dose to 10-dose vials increased store-level wastage in both districts, in Pune from 17.8% to 25.7%.

Modelling studies treat vial size as the main lever. Lee et al. (2010) find that the least-costly presentation depends on daily patient arrivals: for measles vaccine, single-dose vials are cheapest below about two patients a day and 10-dose vials above it. Dhamodharan and Proano (2012) combine binary integer programming with Monte Carlo simulation to choose the vial size and reorder policy that best trade procurement cost against wastage at outreach sessions, noting that wastage depends heavily on the expected session size. Haidari et al. (2015) show that no single vial size suits every setting. Heaton et al. (2017) review the evidence and conclude that doses per container affect coverage, cost and safety together, but that few studies examine these effects jointly. Wedlock et al. (2018) examine single-dose dual-chamber MR devices, and Wedlock et al. (2019) evaluate vial-opening thresholds for measles-containing vaccines. In Mozambique, where the median session size is three, a 30% threshold with 10-dose vials was the only beneficial policy.

A smaller stream optimises what happens within a session. Mofrad et al. (2014) develop dynamic policies for deciding whether to open a multi-dose vial as patients arrive. Mofrad et al. (2018) extend them to non-stationary arrivals and to unvaccinated patients who may return, estimating global savings in the millions of doses a year. Azadi et al. (2020) develop stochastic models of clinic-level vaccine administration and inventory replenishment that minimise open-vial wastage, and find that combining single- and multi-dose vials improves performance. Across all of these studies, the number of children present at a session is the dominant driver of open-vial wastage, but it is treated as given.

2.4 Planning outreach and vaccination sessions

Work on where and when to vaccinate is more recent. Lim et al. (2016) present four coverage models for selecting outreach locations that maximise the population reached, illustrated with data from Bihar. Yang and Rajgopal (2021) combine set covering with vehicle routing to design outreach under uncertainty in population and infrastructure, and allow multi-period revision. During COVID-19, Georgiadis and Georgiadis (2021) integrate daily appointment planning with distribution and inventory in a mixed-integer programme that penalises wasted doses. Tang et al. (2022) solve a bi-objective multi-period problem

trading operating cost against recipients' travel distance with weighted-sum and ϵ -constraint methods and a genetic algorithm. Bertsimas et al. (2022) locate mass vaccination sites by coupling an epidemiological model with a prescriptive optimisation model. Hovav and Tsadikovich (2015) model influenza vaccine inventory and distribution as a network flow problem. These models decide which sites to open and how to assign recipients, but not how often a fixed set of routine sites should operate, and none ties that frequency to open-vial wastage.

2.5 India's immunisation programme

Studies of India's programme emphasise coverage and cost. Gurnani et al. (2018) analyse Intensified Mission Indradhanush and show that cross-sectoral participation can raise coverage among children at high risk. Chatterjee et al. (2016) estimate current and projected UIP costs, and Schueller et al. (2022) estimate the district-level cost of reaching 90% coverage. Their national estimate is US\$1.73 billion for all UIP childhood vaccines, against a 2018 UIP budget of US\$1.17 billion. The electronic Vaccine Intelligence Network (eVIN) has been credited with improving the quality of immunisation data (Bhattacharya et al., 2019). These studies do not treat session frequency as a decision variable, even though it is set explicitly in every sub-centre microplan.

2.6 Positioning of this study

Table 1 summarises representative studies. Three observations emerge. First, network models optimise flows and storage between tiers, and wastage models optimise vial size or the decision to open a vial, but in both the size of a session is an input. Second, the session-planning models developed for COVID-19 choose sites and appointments at large centres, where open-vial wastage matters little. Third, the rule by which Indian microplans actually set session frequency (MoHFW, 2018) is based on injection load alone and has not, to our knowledge, been evaluated against an optimised alternative. This study connects these strands. It treats the frequency of routine outreach sessions at every village as the decision, derives open-vial wastage from that frequency rather than assuming it, prices both wastage and session operations using national norms, and benchmarks the result against the ministry's own rule.

Table 1. Representative studies and the decision each optimises.

Study	Setting	Decision	Method	Objective
Chen et al. (2014)	Niger, Thailand, Vietnam	Flows and inventory across EPI tiers	Linear programming	Maximise fully immunised children
Lim et al. (2022)	Sub-Saharan Africa	Network redesign, vehicles, storage devices	MIP with hybrid heuristic	Minimise cost
Azadi et al. (2024)	Niger	Tiers, vial sizes, presentation	Chance-constrained programming	Maximise coverage and supply ratio
Sripada et al. (2023)	Bihar, India	Multi-tier inventory and transport	Multi-period optimisation	Minimise logistics and shortage cost
Assi et al. (2011), Assi et al. (2013)	Niger	Vial size; removal of a tier	Discrete-event simulation (HERMES)	Scenario comparison
Dhamodharan and Proano (2012)	Outreach, developing countries	Vial size and reorder policy	Integer programming with Monte Carlo	Minimise procurement and wastage cost
Mofrad et al. (2014), Mofrad et al. (2018)	Clinic	Whether to open a vial	Dynamic optimisation	Minimise open-vial waste
Wedlock et al. (2019)	Benin, Mozambique, Niger	Vial-opening threshold	Simulation and economic model	Cost per DALY averted
Lim et al. (2016)	Bihar, India	Outreach locations	Coverage models	Maximise population reached
Tang et al. (2022)	COVID-19	Sites, stations, assignment	Bi-objective MILP, genetic algorithm	Cost and travel distance
This study	Nandurbar, India	Session frequency at every village	MCKP, ϵ -constraint, simulation	Cost of wastage and sessions vs timeliness

III. STUDY SETTING AND DATA

Every parameter in the model is taken from a published public source, listed in Table 3. Where a source gives a range, or where Nandurbar-specific data do not exist, the alternatives are examined in the sensitivity analysis (Section 5.7) rather than fixed by assumption.

3.1 Study area

Nandurbar district had 1,648,295 residents in six talukas at the 2011 Census, of whom 1,372,821 (83.3%) lived in 930 inhabited villages and 69.3% belonged to Scheduled Tribes (Census of India, 2011). The population of each village was taken individually from the Census village tables; the village totals match

the Census rural total for every taluka exactly. Urban areas are excluded because they are served by urban health posts rather than sub-centre outreach. The most recent official projection puts the district's population at 2,042,164 in 2026 (Dhar, 2022, Table 27.1), a factor of 1.2390 over 2011. Because no village-level projection exists, the factor is applied uniformly to every village; the unprojected Census population is tested in Section 5.7.

The Public Health Department of Maharashtra lists 61 PHCs and 293 sub-centres in the district (Public Health Department, GoM, 2025). The taluka-wise distribution used here is from Kaple et al. (2024), whose taluka figures total 61 PHCs and 290 sub-centres. Table 2 summarises the talukas.

Table 2. Villages, births, health infrastructure and the ministry-rule session plan by taluka.

Taluka	Villages	Rural population		Births per year	Sub-PHCs	Villages by ministry-rule frequency					Sessions per month
		2011	2026 (proj.)			centres	Quarterly	Alt. months	Monthly	Twice/month	
Akkalkuwa	189	215,974	267,582	4,316	13	61	78	26	64	21	145.0

Akrani	162	189,661	234,982	3,790	13	50	71	19	48	24	129.2
Nandurbar	149	256,409	317,679	5,124	7	43	33	13	59	44	164.5
Navapur	156	231,134	286,365	4,619	9	46	33	27	70	26	146.5
Shahada	182	346,352	429,115	6,922	14	63	31	23	65	63	212.8
Taloda	92	133,291	165,142	2,664	5	27	27	12	34	19	87.0
District	930	1,372,821	1,700,865	27,435	61	290	273	120	340	197	885.0

Sources: village populations, Census of India (2011); projection factor, Dhar (2022); PHCs and sub-centres, Kaple et al. (2024); births from the rural crude birth rate (Public Health Department, GoM, 2025); frequencies from the rule in MoHFW (2018).

3.2 The current planning rule

Sub-centre microplans set session frequency with RI Form 7 of the Immunization Handbook for Health Workers (MoHFW, 2018, pp. 53–54). The monthly injection load of a village is its monthly target of infants multiplied by 15, the number of injections in the infant and pregnancy schedule. Sessions are then planned as follows: one every alternate month for 1–25 injections a month, one a month for 26–50, and two a month for 51–100. Areas with fewer than 1,000 residents that are not tagged to another site receive a session every quarter, with at least four a year. The handbook also directs that at least one vial of each vaccine be carried to every session (Form 9).

Applied to Nandurbar's projected village populations, the rule assigns 273 villages quarterly sessions, 120 alternate-month, 340 monthly and 197 twice-monthly sessions. This amounts to 885 sessions a month, or 3.05 per sub-centre. We call this the ministry-rule plan and use it as the benchmark throughout. Because the rule depends on population and injection load only, it cannot distinguish a village whose sessions would waste many MR doses from one whose sessions would waste few.

3.3 Demand at session sites

Annual births in each village equal its projected population multiplied by the district's rural crude birth rate of 16.13 per 1,000 (Survey of Causes of Deaths, Rural, 2021;). This gives 27,435 rural births a year. The number of infants surviving to receive later doses is births multiplied by one minus the rural infant mortality rate of 24.61 per 1,000 (same source), giving 26,760.

Expected monthly doses due at the session site of each village are derived from NFHS-5 coverage for Nandurbar (IIPS, 2021):

- BCG: 95.9% of children receive BCG, but 76.3% are born in a health facility, where the birth dose is given before discharge. The remaining 19.6% of births are vaccinated at outreach.
- OPV: three doses at 77.0% coverage (OPV3).
- Pentavalent: three doses at 86.5% coverage (Penta3).
- RVV: three doses given at the same visits as pentavalent (MoHFW, 2019b), so the pentavalent coverage of 86.5% is applied.
- MR: MR1 at 86.5% (MCV1) and MR2 at 22.1% (MCV2).

NFHS-5 reports only third-dose coverage for OPV and pentavalent, so the third-dose figure is applied to all three doses, which slightly understates demand for doses 1 and 2. PCV, fIPV and booster doses are given at the same visits as the vaccines above and are covered by the open vial policy, so their wastage does not depend on session frequency; they are therefore not modelled separately.

3.4 Vaccine presentations and prices

Only the three vaccines excluded from the open vial policy enter the cost of wastage. Vial sizes follow the national wastage assessment and the rotavirus introduction guidelines: BCG 10 doses, MR 5 doses and RVV (Rotavac) 5 doses (MoHFW, 2019a; MoHFW, 2019b). The Government of India does not publish its per-dose procurement prices, so we use the UNICEF Supply Division's awarded prices for the Indian manufacturers that supply these products. These are converted at INR 84.576 per US dollar, the Reserve Bank of India's average for 2024–25 (Ministry of Finance, 2026). The resulting prices are INR 10.19 per dose of BCG, INR 92.19 per dose of MR and INR 59.20 per dose of RVV.

3.5 Session costs

Three costs are incurred for every outreach session under National Health Mission norms. The ASHA receives INR 150 for mobilising children (NHM, 2024). Alternate vaccine delivery is paid at INR 90 per session in ordinary areas, INR 200 in hard-to-reach areas and INR 450 in very hard-to-reach areas. Red and black waste bags cost INR 3 each per session (MoHFW, 2019c). The base case uses the ordinary-area rate, giving INR 246 per session. The hard-to-reach rates are applied to the hilly talukas of Akkalkuwa and Akrani in the sensitivity analysis, because official hard-to-reach designations are not published at village level. ANM salaries are excluded because they are fixed with respect to session

frequency; the ANM's time is instead captured by the workload constraint.

3.6 Workload

No national or state document fixes the maximum number of outreach sessions an ANM can hold in a month. Rather than assume one, we require that the sessions scheduled in each taluka do not exceed the number the ministry's rule itself produces there (Table 2, last column). An optimal plan that satisfies this constraint therefore needs no more ANM time in any taluka than current practice. To show what additional capacity would buy, the budget is multiplied by $\lambda = 1.25$ and 1.5 in Section 5.4.

Table 3. Model parameters and sources.

Parameter	Value	Source
Village populations (930 villages)	Census 2011, by village	Census of India (2011)
Population growth 2011–2026	$\times 1.2390$ (1,648,295 $\rightarrow$ 2,042,164)	Dhar (2022, Table 27.1)
Rural crude birth rate, 2021	16.13 per 1,000	Public Health Department, GoM (2025)
Rural infant mortality rate, 2021	24.61 per 1,000 live births	Public Health Department, GoM (2025)
Coverage: BCG, OPV3, Penta3, MCV1, MCV2	95.9%, 77.0%, 86.5%, 86.5%, 22.1%	IIPS (2021)
Institutional births	76.3%	IIPS (2021)
Vaccines excluded from the open vial policy	BCG, MR, RVV (JE is also excluded but is not in Nandurbar's schedule)	MoHFW (2018, p. 68); Public Health Department, GoM (2025)
Doses per vial: BCG, MR, RVV	10, 5, 5	MoHFW (2019a), MoHFW (2019b)
BCG price	US\$0.1205 per dose (Serum Institute of India, 2023)	UNICEF Supply Division (2025a)
MR price, 5-dose vial	US\$1.090 per dose (Serum Institute of India, 2023)	UNICEF Supply Division (2025b)
RVV price, Rotavac 5-dose vial	US\$0.70 per dose (Bharat Biotech, 2025)	UNICEF Supply Division (2024)
Exchange rate	INR 84.576 per US\$ (2024–25 average)	Ministry of Finance (2026, Table 5.4)
ASHA mobilisation incentive	INR 150 per session	NHM (2024)
Alternate vaccine delivery	INR 90 / INR 200 / INR 450 per session	MoHFW (2019c, Annexure 7)
Waste bags	INR 3 per bag, two bags per session	MoHFW (2019c, Annexure 7); MoHFW (2018)
Session frequencies permitted	Quarterly, alternate months, monthly, twice a month	MoHFW (2018, Forms 7–8)
Workload budget by taluka	Sessions implied by the ministry's rule (Table 2)	Derived from MoHFW (2018)

Note: UNICEF publishes a BCG price only for the 20-dose presentation, which is used for the 10-dose vial supplied in India.

IV. MATHEMATICAL MODEL

4.1 Notation

Sets.

- V : inhabited villages, each a session site, indexed by v ; $V_t \subseteq V$: villages in taluka $t \in T$.

- $K = \{BCG, MR, RVV\}$: vaccines excluded from the open vial policy, indexed by k .
- $F = \{1/3, 1/2, 1, 2\}$: permitted session frequencies per month (quarterly, alternate months, monthly, twice a month).

- O_v : session plans available to village v . A plan $o = (f, g^B, g^M)$ fixes the core frequency $f \in F$ at which sessions are held and the frequencies $g^B, g^M \in F$ at which BCG and MR are offered. RVV is always offered with pentavalent, at frequency f .

Parameters.

- d_{vk} : expected doses of vaccine k due per month at village v (Section 3.3).
- D_v^c : expected doses per month of OPV, pentavalent and RVV, the vaccines offered at every session; $D_v = D_v^c + d_{v,BCG} + d_{v,MR}$.
- n_k : doses per vial; p_k : price per dose (INR); c_t : operating cost per session in taluka t (INR).
- B_t : workload budget of taluka t (sessions per month); λ : budget multiplier.
- ε : maximum permitted dose-weighted mean waiting time (days).

Decision variables. $x_{vo} \in \{0,1\}$ equals 1 if village v follows plan o .

Two plan sets are considered. In the guideline-compliant model every vaccine is offered at every session ($g^B = g^M = f$), as the handbook requires, so $|O_v| = 4$. In the decoupled model BCG and MR may be offered at every r -th session only, for integer r , so $g \in F$, $g \leq f$ and f/g is an integer. This gives $|O_v| = 27$.

4.2 Attendance and open-vial wastage

Children due for vaccine k arrive at a session independently, so the number arriving at one session follows a Poisson distribution with mean $\mu = d_{vk}/\phi$, where ϕ is the frequency at which k is offered. The ANM opens a new vial only when the previous one is exhausted, so a session with N arrivals open $\lceil N/n_k \rceil$ vials. The expected number of vials opened per session is

$$E_k(\mu) = \sum_{m=0}^{\infty} \lceil \frac{m}{n_k} \rceil \frac{e^{-\mu} \mu^m}{m!},$$

and the expected doses opened per month are $Q_k(\phi) = \phi n_k E_k(d_{vk}/\phi)$. The series is evaluated exactly and truncated where the Poisson tail probability falls below 10^{-12} . Expected wastage per month is $Q_k(\phi) - d_{vk}$, and the expected wastage rate is $1 - d_{vk}/Q_k(\phi)$. Proposition 1 (Monotonicity). For any integer $r \geq 2$, $Q_k(r\phi) \geq Q_k(\phi)$. Holding a village's sessions r times as often never reduces the expected number of doses opened.

Proof. Let $N \sim \text{Poisson}(d/\phi)$ be the arrivals at one session held at frequency ϕ . Splitting that interval into r sessions give arrivals $N_1, \dots, N_r$, independent $\text{Poisson}(d/(r\phi))$ variables with $N_1 + \dots + N_r$ having the same distribution as N . The ceiling function is subadditive: $\lceil (a+b)/n \rceil \leq \lceil a/n \rceil + \lceil b/n \rceil$ for non-negative integers a, b . Hence $\lceil N/n \rceil \leq \sum_i \lceil N_i/n \rceil$. Taking expectations and multiplying by ϕn gives $Q_k(\phi) \leq Q_k(r\phi)$. $\square$

Proposition 2 (Bounds). Expected wastage per session satisfies $0 \leq n_k E_k(\mu) - \mu \leq (n_k - 1)(1 - e^{-\mu})$.

Proof. For $m \geq 1$, $\lceil m/n \rceil \leq m/n + (n-1)/n$, and $\lceil m/n \rceil = 0$ when $m = 0$. Taking expectations gives $E_k(\mu) \leq \mu/n + (1 - 1/n)\Pr(N \geq 1)$; the lower bound follows from $\lceil m/n \rceil \geq m/n$. $\square$

Proposition 1 formalises the empirical finding that wastage rises as sessions become smaller (Section 2.3). Proposition 2 shows that each session held for a vaccine can waste at most $n_k - 1$ doses in expectation, weighted by the probability that anyone attends. For small villages, where $\Pr(N \geq 1)$ is well below one, extra sessions add both attendance risk and wastage.

4.3 Timeliness

Due dates are spread evenly through the month, and sessions at frequency f are evenly spaced, $30/f$ days apart. A child who becomes due at a random time therefore waits on average half the interval, $15/f$ days, for the next session at which the vaccine is offered. The dose-weighted waiting time of plan o at village v , in days $\times$ doses per month, is

$$w_{vo} = \frac{15}{f} D_v^c + \frac{15}{g^B} d_{v,BCG} + \frac{15}{g^M} d_{v,MR}.$$

Dividing the district total of w_{vo} by the total doses due, $\sum_v D_v$, gives the mean number of days a due dose waits. The measure rewards timeliness where most doses are due, and it can be computed from the same inputs as the cost.

4.4 Cost of a plan

The expected annual cost of plan o at village v in taluka t is the value of non-OPV doses opened plus the operating cost of the sessions:

$$C_{vo} = 12 \left[\sum_{k \in K} p_k Q_k(\phi_k^o) + c_t f^o \right], \quad \phi_{BCG}^o = g^B, \phi_{MR}^o = g^M, \phi_{RVV}^o = f.$$

Doses that are administered are needed under any plan, so differences in C_{vo} between plans arise from wasted

doses and from sessions. Both C_{vo} and w_{vo} are computed before optimisation for every village and plan, so the optimisation model is linear.

4.5 Optimisation model

$$\begin{aligned} \min \quad & Z = \sum_{v \in V} \sum_{o \in O_v} C_{vo} x_{vo} \\ \text{s.t.} \quad & \sum_{o \in O_v} x_{vo} = 1 \quad \forall v \in V \\ & \sum_{v \in V_t} \sum_{o \in O_v} f^o x_{vo} \leq \lambda B_t \quad \forall t \in T \\ & \sum_{v \in V} \sum_{o \in O_v} w_{vo} x_{vo} \leq \varepsilon \sum_{v \in V} D_v \\ & x_{vo} \in \{0,1\} \quad \forall v \in V, o \in O_v \end{aligned}$$

Constraint (6) assigns one plan to each village. Constraint (7) limits sessions in each taluka to the workload budget. Constraint (8) caps the district's dose-weighted mean waiting time at ε days, and (9) makes the choices binary. The model is a multiple-choice knapsack problem (Sinha and Zoltners, 1979; Kellerer et al., 2004) with $|T| + 1 = 7$ coupling constraints. For Nandurbar it has 3,720 binary variables in the guideline-compliant version and 25,110 in the decoupled version, with 937 constraints in each.

Proposition 3 (Near-integrality of the LP relaxation). Some optimal basic solution of the LP relaxation of (6)–(9) has at most seven villages with fractional plan choices.

Proof. A basic solution of an LP with 937 equality or inequality constraints has at most 937 basic variables. Each of the 930 constraints (6) requires at least one positive variable, and a village with a fractional choice requires at least two. At most $937 - 930 = 7$ villages can therefore be fractional. $\square$

Because only a handful of the 930 villages can be fractional, the LP relaxation is very tight, which explains the fast solution times reported in Section 5.9.

4.6 Solution method and experiments

The cost–timeliness trade-off is traced with the ε -constraint method (Haimes et al., 1971; Mavrotas, 2009). Cost is minimised repeatedly while ε is lowered from 30 days to the smallest value the workload budget allows. That minimum is found by solving (6), (7), (9) with the objective of minimising total dose-weighted waiting time. Each solution is Pareto-optimal: no feasible plan is both cheaper and faster.

The experiments are:

1. Benchmarks: the ministry-rule plan (Section 3.2) and four uniform plans in which every village has the same frequency.
2. Head-to-head comparison: the minimum-cost plan with ε and B_t set to the ministry-rule plan's own waiting time and workload, for both the guideline-compliant and the decoupled model; and the minimum-waiting-time plan at the ministry-rule plan's own cost and workload.
3. Pareto frontiers for workload multipliers $\lambda = 1, 1.25$ and 1.5 .
4. Sensitivity analysis: the head-to-head comparison repeated under alternative sourced values for session cost, population, MR vial size and price, RVV price and exchange rate.
5. Monte Carlo validation: one year of sessions under each plan simulated 2,000 times with Poisson attendance, to check the analytical expectations and measure year-to-year variability.
6. Robustness to over-dispersion: the same plans simulated with negative binomial attendance, with variance-to-mean ratios of 1.5, 2 and 3, since mobilisation by ASHAs may cluster arrivals.

The model was implemented in Python 3.11 with PuLP 3.3.2 (Mitchell et al., 2011) and solved with the open-source CBC 2.10.3 branch-and-cut solver (Forrest and Lougee-Heimer, 2005) to a relative optimality gap of 0.01%. It ran on a two-core Intel Xeon 2.8 GHz cloud machine. The code and data are available as supplementary material.

V. RESULTS

All costs are expected annual costs in INR lakh (1 lakh = 100,000), comprising non-OVP doses opened and session operating costs.

5.1 Validation of the wastage model

The analytical expectations were checked against 2,000 simulated years of sessions under each plan. For the ministry-rule plan, the model predicts 184,709 non-OVP doses opened a year; the simulation mean is 184,697 (95% interval 183,460–185,950). The predicted cost of INR 132.70 lakh matches the simulated mean of INR 132.70 lakh (95% interval 132.19–133.22). The differences are within 0.02% for all three plans (Table 8), confirming the exact wastage formula.

The predicted wastage rates under the ministry-rule plan are 87.0% for BCG, 45.1% for MR and 23.3% for

RVV. The corresponding national service-level figures are 56.8% for BCG, 31.5% for measles-containing vaccine and 40.9% for RVV (MoHFW, 2019a). The ministry's own planning factors assume 50% for BCG and 25% for MR and RVV (MoHFW, 2018, Form 9). The high BCG figure is explained by outreach session size. Because 76.3% of births in Nandurbar occur in facilities, only 5,377 BCG doses a year are due at outreach, an average of 0.51 children per session; 61% of sessions have no child due for BCG. Every child who does attend requires a 10-dose vial. The figure is consistent with the 84.9% average BCG wastage recorded at outreach in Bangladesh (Guichard et al., 2010). MR sessions average 2.74 children, so a 5-dose vial is on average only about half used; the predicted 45.1% lies between the national figure and the 69.7% reported for Bangladesh. The lower RVV rate reflects its larger sessions (6.54 children on average, from three doses per child) and is consistent with the 17.8% store-level wastage reported

for 5-dose RVV vials in Pune (Das et al., 2020). The national RVV figure was measured during the vaccine's introductory phase (MoHFW, 2019a).

5.2 The ministry-rule plan and uniform plans

Table 4 reports the benchmarks. The ministry-rule plan holds 885 sessions a month, gives a dose-weighted mean wait of 15.66 days and costs INR 132.70 lakh a year. Of this, INR 106.58 lakh is non-OVP vaccine opened and INR 26.13 lakh is session costs. It wastes 80,829 doses a year, 43.8% of the doses it opens. Uniform plans show the underlying trade-off. Quarterly sessions everywhere cost INR 90.96 lakh but make a due dose wait 45 days on average. Twice-monthly sessions cut the wait to 7.5 days, but cost INR 195.32 lakh and need 1,860 sessions a month, 2.1 times the ministry-rule workload. Uniform monthly sessions (930 a month) exceed the workload budget in Akalkuwa, Akrani, Navapur and Taloda.

Table 4. Benchmark plans and optimal plans at the ministry-rule plan's waiting time and workload.

Plan	Mean wait (days)	Sessions per month	Cost (INR lakh)			Doses opened per year	Doses wasted per year	Wastage rate		
			Doses	Sessions	Total			BCG	MR	RVV
Ministry-rule plan	15.66	885.0	106.58	26.13	132.70	184,709	80,829	87.0%	45.1%	23.3%
Uniform quarterly	45.00	310.0	81.80	9.15	90.96	138,062	34,182	78.1%	20.7%	9.7%
Uniform alternate months	30.00	465.0	88.26	13.73	101.98	151,310	47,430	82.1%	28.4%	14.0%
Uniform monthly ^a	15.00	930.0	107.11	27.45	134.57	183,528	79,648	86.1%	44.8%	24.8%
Uniform twice a month ^a	7.50	1,860.0	140.41	54.91	195.32	233,946	130,066	88.0%	59.9%	40.4%
Optimal, all vaccines at every session	15.66	809.3	103.17	23.89	127.06	179,080	75,200	86.5%	42.4%	21.9%
Optimal, BCG/MR at a subset of sessions	15.66	884.2	96.49	26.10	122.59	171,095	67,215	85.9%	31.1%	23.4%
Minimum wait at the ministry-rule cost	14.38	885.0	106.52	26.13	132.65	184,295	80,415	86.8%	44.9%	23.5%

^aExceeds the workload budget in at least one taluka.

5.3 Head-to-head comparison with the ministry's rule
With the waiting time and each taluka's workload held at the ministry-rule plan's levels, the guideline-

compliant optimum costs INR 127.06 lakh, 4.3% (INR 5.64 lakh) less. It opens 5,629 fewer doses a year and needs 76 fewer sessions a month (809 against 885).

About three-fifths of the saving comes from vaccine (INR 3.41 lakh) and two-fifths from sessions (INR 2.23 lakh).

The comparison can also be run the other way. Holding cost and workload at the ministry-rule levels, the optimal plan reduces the mean wait from 15.66 to 14.38 days (8.2% shorter), at a marginally lower cost of INR 132.65 lakh. This is also the shortest wait the current workload permits: a further reduction requires more ANM time, not more money.

5.4 The cost–timeliness frontier

Figure 1 and Table 5 show the Pareto frontiers. For $\lambda = 1, 1.25$ and 1.5 the frontiers coincide wherever the workload constraint is slack, and they part only where it binds: at 14.38 days for $\lambda = 1$, 11.56 days for $\lambda = 1.25$ and 9.71 days for $\lambda = 1.5$. The ministry-rule plan lies above the frontier, so it is not Pareto-efficient. The marginal cost of timeliness rises steadily along the frontier. Cutting the mean wait from 30 to 25 days costs INR 1.20 lakh a year per day saved. From 16.5 to 15.66 days, it costs INR 3.65 lakh per day, from 12 to 11 days INR 7.22 lakh, and from 10 to 9.71 days INR 11.30 lakh. Each additional day of timeliness therefore costs about nine times as much near the

capacity limit as at 30 days. The frontier gives planners the price of each improvement, rather than a single recommended plan.

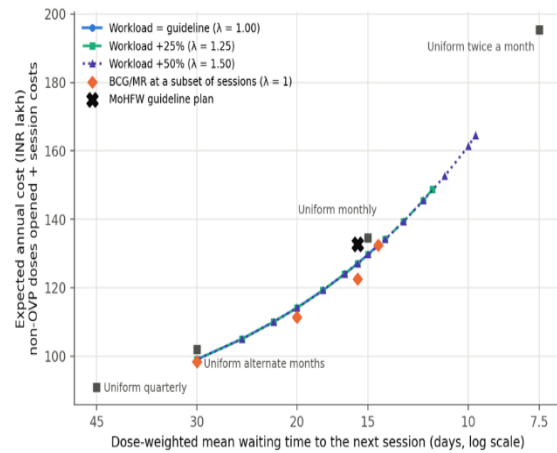


Figure 1. Pareto frontiers of expected annual cost against dose-weighted mean waiting time for three workload budgets. Grey squares are uniform plans, the cross is the ministry-rule plan, and orange diamonds are optimal plans when BCG and MR may be offered at a subset of sessions.

$\lambda = 1.5$ $\lambda = 1$ Table 5. Selected Pareto-optimal plans (beyond the limit).

Max mean waits ϵ (days)	λ	Total cost (INR lakh)	Sessions per month	Doses wasted per year	MR wastage	RVV wastage	Marginal cost (INR lakh/day)
30.00	1.0	99.03	423.0	46,206	26.0%	12.8%	—
25.00	1.0	105.01	508.0	53,348	29.8%	15.0%	1.20
20.00	1.0	114.12	634.2	63,019	35.4%	18.0%	1.82
15.66	1.0	127.05	809.2	75,187	42.4%	21.9%	2.98
14.39 (minimum for $\lambda = 1$)	1.0	132.59	884.5	80,339	44.9%	23.5%	4.36
13.00	1.5	139.29	976.7	86,304	47.5%	25.5%	4.82
12.00	1.5	145.41	1,059.8	91,720	49.8%	27.1%	6.12
11.00	1.5	152.63	1,159.5	97,912	52.2%	29.0%	7.22
10.00	1.5	161.30	1,280.0	105,220	54.7%	31.3%	8.66
9.71 (minimum for $\lambda = 1.5$)	1.5	164.53	1,326.0	107,910	55.5%	32.3%	11.30

Note: Marginal cost is the increase in total cost divided by the reduction in mean wait from the previous row.

5.5 Structure of the optimal plan

Figure 2 compares the frequency assigned to each village by the ministry's rule and by the guideline-compliant optimum at the same waiting time and workload. The optimum redistributes sessions rather than simply reducing them. It gives more sessions to 298 small villages: 224 moves from quarterly to alternate-month sessions and 74 from alternate-month

to monthly. It gives fewer sessions to 150 large villages, which move from twice-monthly to monthly sessions. The frequency of the remaining 482 villages is unchanged.

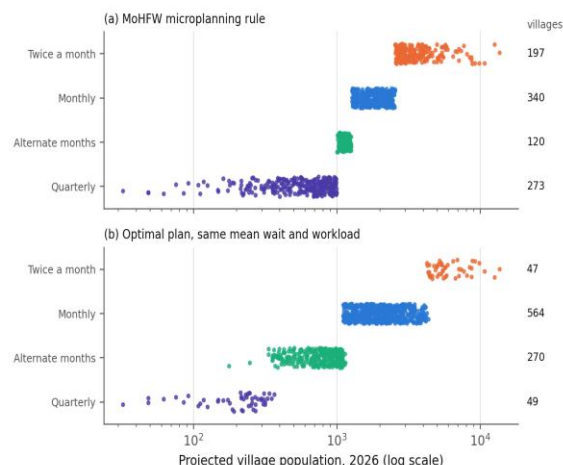


Figure 2. Session frequency of each village under (a) the ministry's microplanning rule and (b) the optimal plan with the same mean waits and workload, against projected 2026 village population. Numbers on the right count villages.

The reason follows from Propositions 1 and 2. In a large village, a second monthly session splits a large

number of arrivals in two, raising MR and RVV wastage and adding a session cost, while shortening the wait for many doses. In a small village on a quarterly schedule, a due dose waits 45 days, and moving to alternate months cuts that to 30 days at the cost of only two extra sessions a year. Per rupee spent, the timeliness gained is greater in the small village. The resulting plan follows a simple population rule. Villages below about 350 residents (2026 projection) remain quarterly; those of about 350 to 1,100 receive alternate-month sessions; those of about 1,100 to 4,300 monthly sessions; and only the largest, above about 4,300, twice-monthly sessions. The ranges overlap slightly between talukas because each taluka's workload budget differs.

Table 6 shows the optimal plan by taluka. The workload budget binds in Akkalkuwa, where 145.0 sessions are used against a budget of 145.0, and is close to binding in Akrani and Taloda. It is slack elsewhere, most of all in Shahada and Nandurbar, the two talukas with the largest villages.

Table 6. Optimal plan (all vaccines at every session) by taluka.

Taluka	Villages by optimal frequency				Sessions per month	Budget (ministry rule)
	Quarterly	Alt. months	Monthly	Twice/month		
Akkalkuwa	12	80	93	4	145.0	145.0
Akrani	23	53	80	6	126.2	129.2
Nandurbar	3	35	98	13	142.5	164.5
Navapur	1	41	108	6	140.8	146.5
Shahada	5	36	126	15	175.7	212.8
Taloda	5	25	59	3	79.2	87.0
District	49	270	564	47	809.3	885.0

5.6 Offering BCG and MR at a subset of sessions

If BCG and MR may be offered at every second or third session, the optimal cost at the same mean wait and workload falls to INR 122.59 lakh, 7.6% (INR 10.12 lakh) below the ministry-rule plan, and 13,614 fewer doses are opened each year. Relative to the guideline-compliant optimum, decoupling adds a further INR 4.47 lakh of savings. The optimum decouples MR in 592 villages: it is offered every second month in 439 villages with monthly sessions, every third month in 63, and monthly in 90 villages with twice-monthly sessions. BCG is decoupled in only 92 villages, because its low price makes the extra wastage cheap. MR sessions then average 4.55 children rather than 2.74, and MR wastage falls from 45.1% to 31.1%.

The district mean wait is unchanged, but its composition shifts. The mean waits for OPV, pentavalent and RVV falls to 14.40 days and for BCG rises to 16.46 days, while for MR it rises from 15.66 to 24.19 days. MR is scheduled at 9–12 and 16–24 months, so an extra week of waiting carries less risk than for the early-infancy doses. Mvundura et al. (2023), however, found that offering such vaccines less often can produce missed opportunities, and the handbook currently directs that every vaccine be carried to every session. Decoupling should therefore be regarded as a policy option to be piloted with monitoring of MR coverage, not as a recommendation this model alone can justify.

5.7 Sensitivity analysis

Table 7 repeats the head-to-head comparison under alternative values, each taken from a published source.

In every case the ministry-rule plan is re-derived under the same values, so each saving compares like with like.

Table 7. Sensitivity of the savings at the ministry-rule plan's waiting time and workload.

Scenario	Ministry-rule	Optimal, all vaccines		Optimal, BCG/MR subset	
	cost (INR lakh)	Cost	Saving	Cost	Saving
Base case	132.70	127.06	4.3%	122.59	7.6%
AVD at hard-to-reach rate (INR 200) in Akkalkuwa and Akrani	136.32	130.53	4.3%	126.21	7.4%
AVD at very-hard-to-reach rate (INR 450) in Akkalkuwa and Akrani	144.55	137.86	4.6%	134.22	7.1%
Census 2011 population, no projection	110.15	106.59	3.2%	103.13	6.4%
MR in 10-dose vials at US\$0.79	148.87	139.72	6.1%	125.48	15.7%
MR in 10-dose vials at US\$0.873	155.69	145.92	6.3%	129.84	16.6%
RVV at the 2019–2024 price of US\$0.85	144.19	138.33	4.1%	134.09	7.0%
Exchange rate INR 87.15/US\$ (calendar 2025)	135.94	130.19	4.2%	125.52	7.7%

The savings are stable across session costs, prices and the exchange rate. They are smaller with the unprojected 2011 population: villages are then smaller, more of them fall below the ministry rule's 1,000-resident threshold, and that plan's mean wait lengthens to 17.88 days, which the optimum must match. Savings are largest with 10-dose MR vials, which make open-vial wastage far more expensive. Comparing rows also bears on vial choice: moving MR from 5-dose to 10-dose vials at the lower 10-dose price would raise the ministry-rule plan's cost by INR 16.17 lakh a year, consistent with the view that vial size should be matched to session size (Lee et al., 2010; Haidari et al., 2015).

5.8 Robustness to variable attendance

Arrivals may be more variable than Poisson, for example if ASHAs mobilise children in groups. Figure 3 shows the simulated distribution of annual cost under Poisson attendance, and Table 8 reports the

simulated annual cost of the three plans with negative binomial attendance of the same mean.

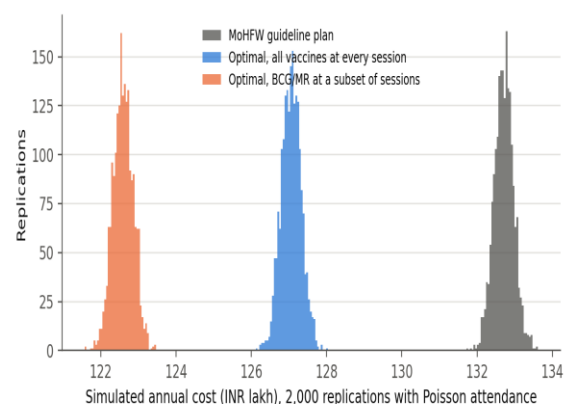


Figure 3. Simulated annual cost of the ministry-rule plan and the two optimal plans over 2,000 years of Poisson attendance. The distributions do not overlap.

Table 8. Simulated annual cost (INR lakh; mean and 95% interval) by attendance variability.

Variance-to-mean ratio of attendance	Ministry-rule plan	Optimal, all vaccines	Optimal, BCG/MR subset	Saving (all vaccines)	Saving (subset)
1.0 (Poisson)	132.70 (132.19–133.22)	127.04 (126.55–127.53)	122.58 (122.08–123.09)	4.3%	7.6%
1.5	131.59 (130.99–132.16)	126.04 (125.47–126.66)	122.15 (121.56–122.77)	4.2%	7.2%
2.0	130.53 (129.83–131.23)	125.08 (124.35–125.75)	121.80 (121.16–122.47)	4.2%	6.7%
3.0	128.52 (127.68–129.35)	123.33 (122.53–124.18)	121.00 (120.24–121.77)	4.0%	5.9%

More variable attendance lowers all three costs, because sessions with no arrivals open no vials. The savings of the optimal plans shrink only slightly, and the 95% intervals do not overlap at any level of variability. The plans were optimised under Poisson attendance, but their advantage over the ministry's rule does not depend on that assumption.

5.9 Computational performance

The guideline-compliant model (3,720 binary variables, 937 constraints) solved to proven optimality in 0.9 seconds, and the decoupled model (25,110 variables) in 5.3 seconds. The LP relaxation was within 0.0047% of the integer optimum for the guideline-compliant model, with fractional values in only two villages, and within 0.0027% for the decoupled model, whose 14 fractional variables lie in at most seven villages, as Proposition 3 predicts. Each point of the Pareto frontier solved in 1–9 seconds. The model can therefore be re-solved interactively during microplanning with free software.

VI. DISCUSSION

6.1 Implications for immunisation planning

The current rule allocates sessions in the wrong direction at both ends. The ministry's rule gives the smallest villages a session only once a quarter, so doses due there wait 45 days on average, and gives every village above about 2,500 residents two sessions a month. The optimisation reverses both choices. Extra sessions in small villages buy a large reduction in waiting for little extra wastage, whereas a second monthly session in a large village mainly splits existing attendance and raises MR and RVV wastage. Moving 298 small villages up a frequency step and 150 large villages down one yields either the same timeliness at 4.3% lower cost with 76 fewer sessions a month, or 8.2% shorter waits at the same cost and workload. A district immunisation officer could adopt the pattern without running the model by using the population bands in Section 5.5. Those bands depend on local birth rates, coverage and prices, however, and other districts should re-derive them.

Timeliness has a rising price, and workload is the ultimate limit. The Pareto frontier puts a price on each improvement. Near current waiting times a day of timeliness costs about INR 3–4 lakh a year across the district. Below 14.4 days no reallocation of the current

workload helps; further gains require more ANM time, and at 10 days each additional day costs about INR 9–11 lakh. This gives district and state planners a quantitative basis for deciding whether additional ANM posts or mobile teams are worth funding, a question the injection-load rule cannot answer.

Vial presentation matters as much as frequency. Supplying MR in 10-dose rather than 5-dose vials would raise the cost of the ministry-rule plan by INR 16.17 lakh a year, despite the lower price per dose, because Nandurbar's MR sessions average fewer than three children. This supports matching vial size to expected session size (Lee et al., 2010; Haidari et al., 2015; Heaton et al., 2017) and suggests that small-session districts are a poor fit for larger MR presentations.

BCG wastage at outreach is structural. With three-quarters of births in facilities, most outreach sessions have no child due for BCG, and any child who attends opens a 10-dose vial. Frequency choices cannot remove this wastage. Because BCG is inexpensive, the model rarely sacrifices timeliness to save it. Reducing it would require a different delivery channel, such as vaccinating home-born infants at the next fixed-site session, which lies outside this model.

Offering MR less often is a promising but contested option. Decoupling MR from the core schedule saves a further INR 4.47 lakh a year at the same average wait, but lengthens MR's mean wait from 15.7 to 24.2 days. The handbook's instruction to carry every vaccine to every session exists to avoid missed opportunities, and Mvundura et al. (2023) observed such missed opportunities where lyophilised vaccines were offered less often. A pilot that tracks MR1 and MR2 uptake would be needed before this could be recommended.

The model fits existing planning processes. It uses only village populations, the district birth and infant mortality rates, survey coverage, sub-centre counts and national price and payment norms. All of these are available to a district immunisation officer, and the model solves in seconds with free software. It could be built into the annual microplanning cycle, and the coverage inputs could be updated from U-WIN and eVIN records rather than periodic surveys.

6.2 Relation to previous work

The results extend the open-vial wastage literature in one direction and the network design literature in

another. Previous wastage studies optimise the vial size or the decision to open a vial, with session size given (Dhamodharan and Proano, 2012; Mofrad et al., 2014; Azadi et al., 2020; Wedlock et al., 2019). Here session size is the outcome of the planning decision. Propositions 1 and 2 give a formal basis for the consistent empirical finding that small sessions waste more (Guichard et al., 2010; Parmar et al., 2010; MoHFW, 2019a). Network design models optimise the tiers above the health facility (Chen et al., 2014; Lim et al., 2022; Yang et al., 2021; Azadi et al., 2024). This model optimises the last step, from sub-centre to village, which those models treat as a single demand node. The use of the ϵ -constraint method to expose a cost-access frontier follows Tang et al. (2022), but applies it to the frequency of routine sessions at fixed sites rather than to the location of temporary ones.

6.3 Limitations

- Timeliness is a proxy for coverage. The model measures how long a due dose waits, not whether the child is eventually vaccinated. Less frequent sessions may increase drop-out, and a model linking session frequency to coverage would strengthen the conclusions.
- Population inputs are projected. Village populations are 2011 Census counts scaled by a district-level projection, because no more recent village enumeration exists. The unprojected population is tested in Section 5.7, and the analysis should be repeated when the next Census is published.
- Villages are treated as separate session sites. In practice small hamlets are often tagged to a neighbouring site. Grouping villages would enlarge sessions and reduce wastage further, but requires road distances that were not available.
- Some inputs are proxies. NFHS-5 reports only third-dose coverage for OPV and pentavalent, and district estimates carry sampling error. Vaccine prices are UNICEF contract prices, because Indian procurement prices are not published, and the BCG price is for a 20-dose vial. The workload budget is derived from the ministry's rule rather than from measured ANM capacity, and the taluka distribution of sub-centres (290) is slightly older than the current district total (293).

- Hard-to-reach designations are not published at village level. Their effect was bounded in the sensitivity analysis by applying the higher AVD rates to the two hilly talukas.
- Seasonality and cold-chain capacity are not modelled. Monsoon access, seasonal migration and PHC cold-chain space are outside the model. Because the optimal plan opens fewer doses than the ministry-rule plan, it does not add to cold-chain load.
- Single-district evidence. The magnitude of savings will differ in districts with larger villages or higher institutional delivery. The method, however, transfers directly.

VII. CONCLUSION

This paper modelled a decision that every sub-centre microplan in India makes each year, how often to hold an outreach session in each village, as a multiple-choice knapsack problem. It trades the cost of open-vial wastage and session operations against timeliness under taluka workload budgets. Expected wastage was derived exactly under Poisson attendance, and splitting sessions more finely was proved never to reduce it. The linear-programming relaxation was shown to be nearly integral, and the cost-timeliness frontier was traced with the ϵ -constraint method.

Applied to all 930 villages of Nandurbar with public data and national norms, the model shows that the ministry's microplanning rule is not Pareto-efficient. At the same timeliness and workload, an optimal plan costs 4.3% less, and at the same cost and workload it shortens waits by 8.2%. It achieves this by giving small villages more sessions and large villages fewer. Offering MR at a subset of sessions raises the saving to 7.6%, at the price of longer MR waits that would need to be monitored. The results were validated by simulation, held across every sensitivity scenario and under over-dispersed attendance, and were obtained in seconds with free software.

Four extensions would strengthen the work: linking session frequency to coverage and drop-out, grouping hamlets into shared sites using road distances, modelling uncertainty in births and attendance through stochastic or robust optimisation, and applying the model to other districts to test whether the population bands found here generalise.

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