Coordination strategies to improve PCR laboratory testing scale up in Nepal: an analysis based on COVID-19 response

Hannah Bakker[a] and Arunkumar Govindakarnavar[b]and Parvathy K Krishnakumari[c] and Joaquim Gromicho[d] and Fannie L. Côté[e] and Nadia Lahrichi[e] and Priya Jha[b] and Saugat Shrestha[b] and Rashmi Mulmi[b] and Nirajan Bhusal[b] and Deepesh Stapith[b] and Runa Jha[f] and Lilee Shrestha[f] and Dhamari Naidoo [g] and Reuben Samuel[g] and Victor del Rio Vilas[h]

[a] Health Care Lab, Karlsruhe Institute of Technology, Karlsruhe, Germany [b] World Health Organization Country Office for Nepal, Kathmandu, Nepal [c] Analytics for a Better World, Amsterdam, The Netherlands [d] University of Amsterdam & ORTEC, Zoetermeer, The Netherlands [e] CIRRELT & Polytechnique Montréal [f] National Public Health Laboratory, Kathmandu, Nepal [g] World Health Organization South East Asia Regional Office (WHOSEARO), New Delhi, India [h] UK-Public Health Rapid Support Team, UK Health Security Agency, London, UK

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The study explores the impact of insufficient laboratory capacity and uncoordinated sample distribution on the stress experienced by individual laboratories during high pandemic activity, using the context of SARS-CoV-2 testing in Nepal in 2021. Rapidly expanding diagnostic capabilities in response to increased testing demand resulted in localized strain, causing staff overtime and prolonged wait times. The objective is to determine whether stress on laboratories stems from overall capacity issues or imbalanced sample distribution due to a lack of coordination.

Examining the potential of coordinated sample transfers between laboratories, the study aims to balance workloads and reduce wait times in a simplified model based on Nepalese data. The current diagnostic network in Nepal is segmented by public and private labs and provincial borders with limited coordination. The study evaluates the effectiveness of comprehensive cooperation mechanisms, emphasizing simple, implementable strategies to facilitate coordination and reduce communication channels. Validation experiments simulate various demand fluctuations and capacity shortages.

Case study results in the model environment suggest that central coordination significantly enhances diagnostic network performance during crises. Identifying one or two strategic partners for each lab for sample transfers proves effective. The findings provide policymakers insights into operational coordination implementation.

Evidence before this study

Literature on the efficient design of diagnostic networks focuses on coordinating systems in a steady state. Investigating strategies to efficiently respond to disease outbreaks and improve the system's performance in times of distress has rarely been explored. The only framework assessing the potential of ad hoc transfers between lab-

oratories during times of high demand for diagnostic capacities evaluates the potential of an omnipotent centralized coordination authority. No studies evaluating simpler forms of sample transfer coordination have been found. Several studies evaluate the expansion of diagnostic capacities in response to the COVID-19 pandemic. However, up to this point, none of these studies evaluates the potential benefit of coordinated sample transfers. Search terms included "COVID-19 laboratory capacity", "COVID-19 testing coordination", and "diagnostic testing logistics" on Google Scholar.

Added value of this study

We demonstrate that during the 2021 COVID-19 outbreak in Nepal, the imbalanced distribution of test samples across laboratories rather than an overall capacity shortage led to the over-utilization experienced by individual laboratories. In a simplified model environment, we test simple strategies for collaboration between individual laboratories regarding coordinated sample transfers.

Implications of all available evidence

Our study demonstrates the potential of fostering cooperation between laboratories during peak demands for diagnostic capacities. In this regard, establishing a few strategic partnerships between laboratories rather than a centralized coordination system suffices to leverage a significant proportion of the potential benefit from sample transfer strategies. While challenges regarding the practical implications remain, the study clearly outlines forms of collaboration between laboratories to be explored.

KEYWORDS

1. Background

Diagnostic testing is a crucial component of outbreak control (World Health Organization, 2020) and has received significant attention in worldwide and national efforts to contain the spread of SARS-CoV-2 during the ongoing COVID-19 pandemic. The PCR-based test to detect SARS-CoV-2 requires trained personnel, strict safety procedures, and equipment only found at specialized diagnostic laboratories. The sudden increase in demand for this test led to the quick expansion of the diagnostic network in several countries, including Nepal, the focus point of the present study. An increasing number of public laboratories were established across the nation and equipped with the necessary machinery to perform PCR testing. At the same time, several private laboratories started operating as high demand for diagnostic testing became a business opportunity. As of November 2021, the resulting diagnostic network possesses significant capacity to perform PCR-based COVID-19 testing and attend to national needs. Yet, particularly during temporally and geographically confined disease outbreaks, individual laboratories face overwhelming sample numbers, resulting in overworked staff and long waiting times for test results.

This raises the question to which degree the over-utilization of individual laboratories during phases of high pandemic activity results from insufficient laboratory capacity and to which degree it stems from an imbalanced distribution of sample numbers among individual laboratories due to insufficient - or non-existent - coordination.

Central coordination of test samples is challenging to implement as it requires consistent data reporting by several stakeholders and the organization of ad-hoc sample transfers. This investigates its potential in the specific situation of Nepal through a simplified modeling environment. This allows decision-makers to evaluate its theoretical potential and simulate the benefits of different degrees of cooperation, e.g., between different jurisdictions or between private and public laboratories and several different coordination strategies.

In response to COVID-19, many countries rapidly increased their diagnostic capacity. Several studies evaluate the effectiveness of these scale-ups and report lessons learned. A common observation was the severe geographical imbalance of testing capacities. Furthermore, a lack of trained personnel and equipment and infrastructural challenges in resource-constrained areas provided immense constraints in the expansion of testing capacities, e.g., in Indonesia (Hendarwan et al. (2020)), Ghana (Acheampong et al. (2021)), and Ethiopia (Abera et al. (2020)). Several studies suggest partnerships with private laboratories as a potential opportunity to increase capacities further Abu-Dayyeh et al. (2023); Diarra et al. (2022).

While the literature on the efficient design of diagnostic networks focuses on coordinating systems in a steady state, investigating strategies to efficiently respond to disease outbreaks and improve the system's performance in times of distress has rarely been explored. For example, Jónasson, Deo, and Gallien (2017) reported diagnostic supply chains for early infant HIV detection in Sub-Saharan Africa. To the best of our knowledge, the only work focusing on the in-time coordination of samples is presented by Bakker, Bindewald, Dunke, and Nickel (2023). The authors present a rolling horizon procedure in which they determine near-optimal sample transfers in each period solely based on currently available data. They determine optimal transfers in every period by solving a mixed-integer linear program that requires up-to-date data inputs from a large number of laboratories to determine the transfers. In contrast, the focus of this study lies in evaluating the potential of coordination in the specific case of Nepal by using simple coordination strategies.

2. Methodology

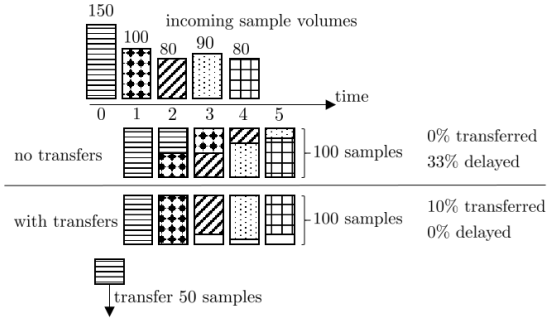


Figure 1. Visualization of the potential of sample transfers to reduce testing delays.

Laboratories in Nepal performing PCR testing for SARS-CoV-2 process the majority of incoming samples in a first-in-first-out manner (FIFO). The example depicted in Figure 1 shows how the FIFO policy contributes to an overload of samples in one period, causing delays in several subsequent periods. Consider the following setting:

the planning horizon is divided into periods of fixed length, e.g., days or half-days. Test samples arrive at a laboratory throughout one period to be processed within the next period. Each laboratory has a fixed and known processing capacity per period. The figure shows one laboratory over the course of 5 periods with a fixed processing capacity of 100 samples per period. The incoming sample volumes throughout the 5 periods are 150, 100, 80, 90, and 80. The laboratory can fully process the resulting total of 500 samples within the upcoming 5 periods. However, without the ability to transfer samples to other laboratories, the FIFO policy, together with the high number of test samples arriving in the first period, leads to a mitigation of delays throughout the planning horizon. In the end, 33% of the incoming 500 samples could not be processed within the next period. Meanwhile, the figure illustrates that if those 50 samples that exceeded the capacity in period 1 were transferred to another laboratory, the number of delayed samples could be reduced to zero. Therefore, transferring only 10% of the test samples may decrease the waiting time for test results for 33% of the test samples. The example exhibits a central idea behind the subsequently studied coordination strategies. If one manages to consistently avoid backlog from building up by transferring samples away from laboratories that are under distress to laboratories with spare capacities, one may significantly reduce the total stress in the system with relatively few logistical operations.

2.1. Simulation Model

We follow the framework presented in Bakker et al. (2023) to analyze the potential of coordinated sample transfers. The framework consists of a rolling horizon procedure that simulates the waiting times of test samples in the laboratory entry queue and their movement through a diagnostic network. The framework operates based on the following assumptions. Test sample counts that arrived throughout one period are reported to a coordinating entity at the end of this period. In each period, each laboratory has a known, fixed processing capacity. Incoming samples enter the entry queue at the laboratory and are processed in a strict FIFO manner. There is a defined target regarding the maximum number of periods in which samples should be processed. A transfer may be issued only if this target is missed due to insufficient processing capacities. It is assumed that transfers are possible between two periods. For example, when periods equal workdays, transfers should be feasible overnight. The set of laboratories to which samples may be transferred is predefined and depends on the respective travel distance between these two laboratories and the workload of the receiving laboratory. Transfers are only initiated if the receiving laboratory reports sufficient capacity to process all additional samples within the target time.

2.2. Performance Measurement

The turn-around-time (TAT), the time between the collection of the sample and the availability of results at the laboratory (Jónasson et al. (2017)), is a central performance criterion for diagnostic networks. However, as the present analysis only considers the waiting time at the laboratory plus the potential travel time resulting from a transfer, the TAT cannot be accurately measured. However, as this waiting time directly affects the TAT, minimizing the waiting time for processing will directly reduce the TAT.

Following the work of Bakker et al. (2023), we deliberately chose not to minimize

the waiting time directly. As every intervention from a coordinating entity involves coordination, communication, and logistical handling efforts, we would only be willing to undertake such investments to obtain improvements beyond a certain target level. For example, if the average waiting time was 6 hours, we would not be willing to initiate a transfer to reduce it to 1 hour as 6 hours is still a reasonable waiting time. However, we would be willing to invest in reducing it from 24 hours to 6 hours. To capture this, we set a target processing time and measure the performance of our coordination scheme based on the number of samples that cannot be processed within that time. We consider these samples as "delayed" and report the fraction of delayed samples over the considered planning horizon.

2.3. Insufficient Capacity vs. Insufficient Coordination

The simulation model does not include the option of overtime. Thus, if the total number of test samples exceeds the total capacity in an area, there is nothing the coordination strategy may do to avoid delay. Thus, the reported fraction of the delayed samples has little significance as the cause of the delay - overall insufficient capacity or insufficient coordination - cannot be determined. Central coordination of samples can only improve the latter. Therefore, we derive upper and lower bounds for the delay that is achievable in a given scenario based on the respective sample volumes and capacities (ref. Section 3). The upper bound on the delay is derived by running the simulation while prohibiting any transfers. We also refer to this as *No Coordination*. The lower bound is obtained by determining the currently optimal transfers per period via the mixed-integer linear program provided by Bakker et al. (2023). The latter result can be considered a lower bound on the delay and an upper bound on what can be achieved by solely coordinating transfers without increasing the capacity. It is a lower bound because resources for communication, coordination, and logistical operations are assumed to be unrestricted. We refer to this as *Unrestricted Coordination*. All simplified coordination rules will be measured against these two figures.

3. Case Study: SARS-CoV-2 Nepal 2021

Before we evaluate the potential of coordinating sample transfers, we first explore the diagnostic situation in Nepal as experienced during the SARS-CoV-2 pandemic in 2021. We use this analysis to get an overview of the relevant conditions and factors influencing the diagnostic network in Nepal.

Diagnostic testing in Nepal takes place at different health facilities. Sample collection is done at public and private hospitals and general health facilities, some of which have an on-site laboratory. Furthermore, several laboratories offer on-site sample collection. Lastly, there are sample collection events initiated by private laboratories where mobile units temporarily move into communities to conduct sample collection. Whenever samples are not collected directly at a laboratory, a sample transfer must be initiated. Currently, such transfers are initiated ad hoc, and sample numbers are reported only after they have been processed at the laboratory.

The data used in the case study is obtained from the daily situation reports published by Nepal's Ministry of Health and Population (MoHP) on their website (`https://covid19.mohp.gov.np/situation-report`) (Ministry of Health and Population, n.d.). Our analysis includes the reports from May 1st to November 20th, 2021, a period capturing different levels of pandemic activity. Amongst other infor-

mation, these reports provide the number of processed samples and the number of positive test results reported by individual laboratories. The reported numbers fluctuate throughout the week, which stems from delays in reporting results rather than actual fluctuations in the test sample numbers. Therefore, in all further analyses, we use the 7-day moving averages of the reported numbers to smooth out such artifacts.

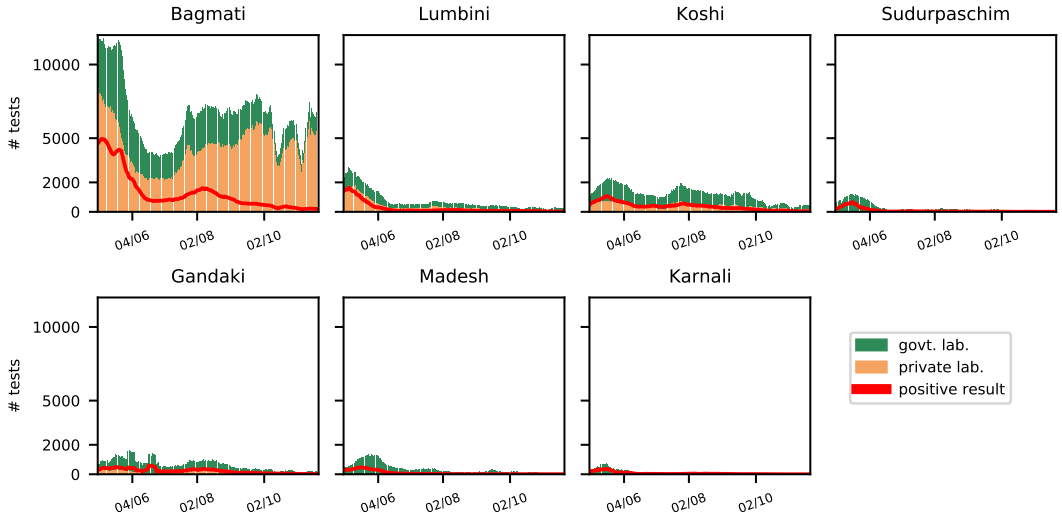


Figure 2. 7-day moving average of reported test sample numbers and positivity rates per province

Nepal is divided into 7 administrative provinces that are demographically distinct regarding population count and relative wealth. During the SARS-CoV-2 pandemic, Nepal's diagnostic capacity has increased significantly in public and private laboratories. In particular, many private laboratories have been established in the capital, Kathmandu, in Bagmati province. The number of test samples reported between May 1st and November 20th, 2021, across provinces and laboratory type is depicted in Figure 2 and Figure 3. Figure 2 shows that most samples are processed in Bagmati, both for private and public laboratories. This is primarily due to the fact that it has the highest population. Consequently, the situation in Bagmati province dominates what is observed on a national level. Private laboratories only exist in Bagmati, Lumbini, Koshi, and Gandaki. These four provinces account for 65% of Nepal's population (United Nations Population Fund, 2017). Figure 2 furthermore shows that in Sudurpaschim, Madesh, and Karnali, the number of performed tests after the delta wave from April 2021 to July 2021 practically dropped to zero. To get an adequate overview of the effectiveness of specific coordination strategies, we have to consider provinces individually. As each jurisdiction has its own funding, cooperation of testing facilities with laboratories outside their respective districts does not occur. To further assess the relevance of private laboratories regarding the national testing activity, Table 1 displays the total test volumes and the respective shares of tests performed by private and public laboratories. As Figure 2 already indicated, the share of private tests increases from 47.2% in May to 72.5% in November. However, looking at the totals, it is clear that this increased share results from the fact that the number of tests performed by public laboratories decreased more significantly than the tests run by private laboratories. public laboratories reported a total of approx. 271K tests in

May, reducing to 60K tests in October. Meanwhile, private laboratories report approx. 243K tests in May and only reduce to approx. 158K in October. Thus, while public laboratories reduced their test volume by 77.9%, private laboratories only reduced the numbers by 35.0%. Table 2 shows that this decline in the share of public tests can be mainly attributed to the testing activity in Bagmati, where the share of public tests decreases from 42.8% to 23.8%. It must be emphasized that individuals usually pay for tests at private laboratories. Thus, this testing option is almost exclusively accessible to wealthier parts of the population. Furthermore, it must be noted that during this period, the national testing strategy was altered in the sense that a charge for voluntary testing was introduced at public laboratories, which was the same amount charged at private laboratories. This led to an increase in voluntary testing at private laboratories and a decrease in testing at public laboratories.

Table 1. Reported sample volumes per month for government and private laboratories on a national level.

	May	June	July	August	September	October
Tot.	513516	272982	256639	309891	287089	217428
Govt	270912 (52.8%)	166348 (60.9%)	130507 (50.9%)	138320 (44.6%)	104349 (36.4%)	59826 (27.5%)
Priv.	242604 (47.2%)	106635 (39.1%)	126131 (49.2%)	171570 (55.4%)	182740 (63.7%)	157601 (72.5%)

Table 2. Fraction of sample volumes for different phases per province reported by government and private laboratories (govt% / private%).

	Bagmati	Gandaki	Karnali	Lumbini	Koshi	Madesh	Sudurpaschim
May- Jun	42.8 / 57.2	79.3 / 20.7	100.0 / -	43.3 / 56.7	65.4 / 34.6	100.0 / -	100.0 / -
Jul-Aug	37.1 / 62.9	70.1 / 29.9	100.0 / -	46.6 / 53.4	64.3 /35.7	100.0 / -	100.0 / -
Sep-Oct	23.8 / 76.2	63.6 / 36.4	100.0 / -	48.8 / 52.0	60.5 / 39.5	100.0 / -	100.0 / -

Another difference can be seen in Figure 3. It shows that test positivity rates (TPR) are higher for public laboratories. Over the observed period, the TPR of public laboratories is, on average, 6.27% higher than that of private laboratories. The maximum difference of 12.14% in TPR was observed on November 2nd, 2021, while the minimum difference of -6.3% was observed on June 6th, 2021. Furthermore, the share of private testing increases after June 2021. A look at Figure 2 shows that the share increases because government testing decreases with decreasing case numbers while private testing remains at a relatively stable level. This may be because public laboratories process all test samples from official case identification, contact tracing, and surveillance efforts. Therefore, they receive a lot of samples from clinically symptomatic cases. Thus, they receive larger sample volumes when many people are sick and are more likely to obtain positive samples. In contrast to public laboratories, tests at private laboratories must be paid for by individuals, opening this testing opportunity almost exclusively to wealthier parts of the population. These people are more likely to require tests for traveling or an earlier release from quarantine. Additionally, private laboratories account for the predominant part of the active testing, i.e., by mobile sample collection facilities actively moving into communities. The latter two points may not only contribute to the fact that their test volumes are less affected by the overall pandemic situation, as observed in Figure 3.

In conclusion, the data shows that to get a comprehensive picture of the effectiveness of different coordination strategies in Nepal one must take the distinction between individual provinces and public and private laboratories into account.

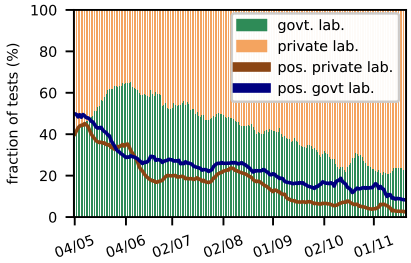


Figure 3. Share total number of tests performed by public and private laboratories as well as respective positivity rates

4. Exploratory Experiments

The analysis in Section 3 has shown that to evaluate the potential of centralized coordination strategies for test samples, we must take the distinction between private and public laboratories into account. Furthermore, we need to evaluate the situation for each province individually, as provinces are extremely heterogeneous regarding their diagnostic capacities and geographical distribution, which affects the feasibility of transfers between individual laboratories within a short time frame. Open questions resulting from this analysis include

(1) Is central coordination of test samples an effective means to improve the performance of the diagnostic system in Nepal, or are insufficient diagnostic capacities and geographical distances obstacles that cannot be overcome by coordination?
(2) Should one encourage cooperation between laboratories across provincial borders?
(3) Should one encourage cooperation between public and private laboratories?
(4) Which of the above two forms of cooperation yields greater potential and should, therefore, be prioritized?

Besides these questions that come as a direct result of the situation in Nepal, we aim to answer the overlying question regarding the potential of implementable coordination strategies that do not require persistent data flow to one omniscient coordinating authority but require communication between fewer stakeholders on a local level.

Evaluating different coordination strategies on different levels of cooperation (inner-province, cross-province, or public-private) results in a larger number of potential combinations. Thus, we perform preliminary experiments on a singular representative scenario to obtain answers to questions (2)-(4) and identify promising coordination strategies. We validate our findings on a broader set of scenarios in Section 5.

4.1. Representative Scenario

We derive a representative scenario for the preliminary experiments from the data provided in the situation reports (Ministry of Health and Population, n.d.). As we are interested in reducing the over-utilization of individual laboratories during periods of distress, we base our analysis on data reported during the Delta (B.1.617.2) wave of the SARS-CoV-2 pandemic hitting Nepal in May and June 2021. Therefore, we define the planning horizon of our scenario from May 3rd to July 1st, 2021. Each of the 57 days represents one period of our planning horizon.

Incoming sample numbers are reported by laboratories only after they have been processed. Information regarding their origin, collection date, or arrival date at the laboratory is not available in the reports and is difficult to retrieve. For our representative scenario, we take the 7-day moving averages of the reported throughputs as incoming sample volumes. The development of the accumulated sample numbers over this planning horizon is depicted in Figure 4 for public and private laboratories, respectively. We test how more substantial fluctuations of the incoming sample numbers affect our results in Section 5.1.

As no data on the origin of test samples is available, we allow for coordination and transfers of test samples at the laboratory entry. The assumed procedure is that at the end of each period, laboratories report the incoming sample volumes and may transfer samples to another laboratory if the samples exceed their prospective processing capacity during the target time. According to officials, the political target for the TAT is 24 hours. As in the current part of the analysis, we only consider the time required for shipment and the waiting time at the entrance of the laboratory. It is evident that to not exceed a 24-hour TAT, the processing of samples at the laboratory must take place on the next day at the latest - otherwise, a TAT of 24 hours cannot be achieved, and we will count the sample as "delayed". Transfers are thus assumed to take place overnight. Distances between laboratories are measured in travel times obtained via Google Maps API. To ensure that transfers are feasible, we set an upper limit on the driving time of 8 hours.

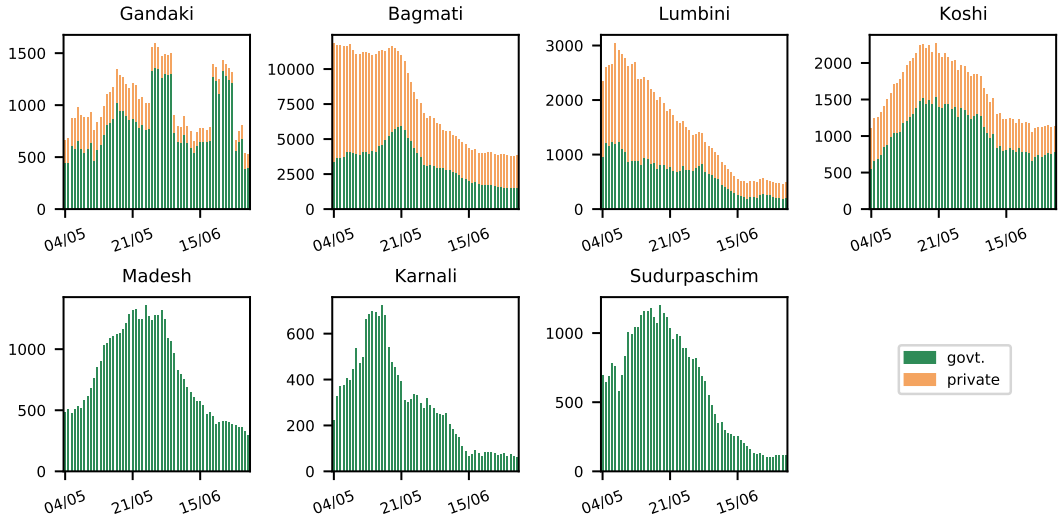


Figure 4. Development of sample volumes arriving at public and private laboratories in validation scenario

Data on the actual processing capacity of individual laboratories is not available. Therefore, the processing capacities of individual laboratories had to be estimated. We set the daily capacity to 80% of the maximum reported throughput per day. In addition to expert validation of the resulting capacities, we confirmed them with the help of a simulation study run by Fannie L.Côté and Nadia Lahrichi from Polytechnique Montréale. We evaluate the effect of different capacity estimates in Section 5.3. Figure 5 depicts the overall capacity shortage or excess. The Figure shows that the total testing capacity for most provinces consistently exceeded the total throughput for privately

and public laboratories. As a result, one may conclude that there is enormous potential in a coordinated distribution of test samples. We will subsequently investigate the degree to which this holds when considering the geographical dispersion of demand and capacity within provinces.

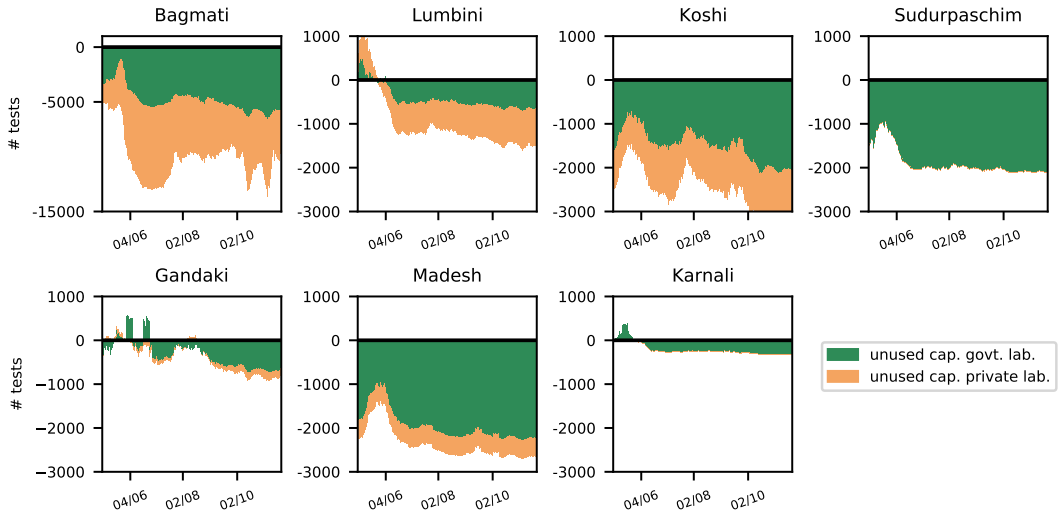


Figure 5. Accumulated capacity estimates minus daily throughputs per province

4.2. Results

4.2.1. Potential of Coordination and Cooperation

In the first step, we derive lower and upper bounds on what is achievable by centralized coordination of test samples in the representative scenario described in Section 4.1. We, therefore, first run the simulation without allowing any form of transfer or coordination between laboratories (*No coordination*). Then, in a second step, we allow for centralized transfers and use the procedure to identify near-optimal transfers in each period presented by Bakker et al. (2023) (*Unrestricted coordination*). We run the procedure allowing for different levels of cooperation, e.g., only between public laboratories within the same province, only between public laboratories but on a national level, between public and private laboratories only within the same province, and between public and private laboratories on a national level. Generally, transfers are only possible when the driving time between two laboratories is less than 8 hours.

Before we move on to the results, let us reconsider what we observed in Figure 5, which depicts the excess processing capacity throughout the planning horizon. The overall capacity per province exceeds the total number of test samples in Bagmati, Koshi, Madesh, and Surdurpaschim. Consequently, we should expect that with sufficient flexibility regarding the transfer of test samples a central coordination strategy should be able to completely avoid any delays. However, in practice, even within one province, driving times between two individual laboratories may exceed the 8-hour limit. For example, in Sudurpaschim, the driving time between the Kamalbazar RT-PCR laboratory and the Mahakali Zonal Hospital Laboratory is 10 hours and 46

minutes. We wish to see to which degree local capacities within sufficient proximity suffice to process all collected samples in time.

Table 3 displays the results for all laboratories and for public and private laboratories separately. No coordination implies that samples must be processed at the laboratory where they arrive initially, even if that implies long waiting times. In the given scenario, this results in 21.4% of the samples not being processed within the next 24 hours on a national level. This fraction is slightly larger for public laboratories (23.6%) than it is for private laboratories (18.7%). However, it is interesting to see that private laboratories - with the estimated capacities and reported sample volumes - will not process almost every 5th sample within the next 24 hours. This number is, of course, only a very rough estimate of reality but indicates that the private laboratories may experience phases during which they struggle to process all collected samples in a timely manner.

Table 3. Fraction of delayed samples total (public/private) per province for different levels of coordination and cooperation.

	No Coordination	**Unrestricted Coordination (max. 8 h)**			
	-	only within province		nationwide	
		pub.	pub. & priv.	pub.	pub. & priv.
Bagmati	15.2 (16.7/14.1)	0.2	0 (0/0)	0	0 (0/0)
Gandaki	41.8 (38.2/55.4)	0	0 (0/0)	0	0 (0/0)
Karnali	30.8 (30.8/-)	25	25 (25/ -)	0	0 (0/0)
Lumbini	26.1 (16.4/33.5)	7.7	4.6 (3.2 /5.6)	0	0 (0/0)
Koshi	22.9 (25.1/18.8)	0	0 (0/0)	0	0 (0/0)
Madesh	19.1 (19.1/ -)	0	0 (0/ -)	0	0 (0/0)
Sudurpaschim	47.7 (47.7/ -)	28.4	28.4 (28.4/ -)	0	0 (0/0)
National	**21.4 (23.6/18.7)**	**4.1**	**2.3 (3.6/0.8)**	**0**	**0 (0/0)**

Furthermore, Table 1 shows the maximum reduction in the fraction of delayed samples obtained by enabling sample transfers between laboratories for different levels of cooperation in the given scenario. The results are maxima in the sense that the central coordination strategy deployed in Bakker et al. (2023) possesses full information and is assumed to have access to unlimited logistical resources. Thus, any remaining delay is not the consequence of insufficient coordination but of insufficient capacity within sufficient proximity of the respective demands. Already allowing for cooperation only between public laboratories of the same province can reduce the fraction of delayed samples from 21.4% to 4.1% on a national level. The provinces Karnali, Lumbini, and Sudurpaschim simply do not possess sufficient capacity to process all samples during all times of the scenario, as is also visible in Figure 5. This is not altered by including private laboratories in the coordination strategy since, for example, Karnali and Sudurpaschim do not have private laboratories. In fact, including private laboratories does not significantly reduce the stress put on public laboratories in any other province than Lumbini. However, delays in these provinces can be avoided entirely when allowing transfers between public laboratories across provincial borders. In the given scenario, allowing for transfers across borders effectively reduces the delays to zero. This is a fascinating observation, namely that during the entire planning horizon and for all public laboratories, there was another public laboratory with sufficient free capacity to take on all samples within an 8-hour drive. Cooperation across provincial borders occurred, particularly between laboratories from Karnali, Lumbini, and Sudurpaschim. We observed that transfers between these three provinces occurred between all provinces in both directions. The actual transfers between laboratories are listed in Table 5. They are plausible when looking at a map, e.g., Kamalbazar Municipality PCR Lab in Sudurpaschim is very close to the Karnali border. The results indicate

that communication between the healthcare providers of these provinces should be encouraged in the future.

The reduction in the delays comes at a price in terms of logistical efforts. Table 4 displays this effort for cooperation between public laboratories across provinces. It shows the total fraction of transferred samples and the number of individual transfers necessary, within and outside provinces, to achieve this result over the 57-day planning horizon. Furthermore, the fraction of the transferred samples is consistently below 6%. So is the total number of individual transfer operations. Each operation transfers an arbitrary portion of samples from one laboratory to another. There are 495 transfers over 57 days, which implies an average of 8.7 transfers per day. The largest number of transfers is required in Bagmati, with 183 operations over the planning horizon, averaging 3.2 transfers per day. Meanwhile, 80% of the transfers take place within the same province. Out-of-province transfers play the largest role in Gandaki, Karnali, and Lumbini, with 43.6%, 59.2%, and 45.2% of the overall transfers, respectively.

Table 4. Logistical efforts associated with cross-province cooperation between government laboratories.

	Transferred samples (%)	# Transfers	inner-province	outer-province
Bagmati	2.6	183	160	23
Gandaki	4.4	48	27	21
Karnali	5.1	27	11	16
Lumbini	3.3	42	23	19
Koshi	2.9	64	64	0
Madesh	3.0	75	73	2
Sudurpaschim	5.9	56	39	17
national	**3.3**	**495**	**397**	**98**

4.2.2. Simplified Transfer Strategies

Now, given the above results, we see that relatively small logistical efforts can obtain tremendous improvement. Thus, the bottleneck regarding centralized sample transfers does not lie in the actual logistics but rather in the communication and coordination required upfront. Three transfers in a province like Bagmati per day is not much. However, organizing them between three arbitrary locations ad hoc based on persistent data inflow from all individual laboratories very much bears a challenge. Thus, to obtain coordination strategies that are feasible and do not put additional stress on a system already at its limits, we seek strategies that work more simply and require less communication as well as less flexibility from logistic carriers. Therefore, we simulate

Table 5. Cross-provincial transfers of test samples in the representative scenario.

—	Source		Destination
Province	Laboratory	Province	Laboratory
Karnali	Surkhet Provincial Hospital	Sudurpaschim	Dadeldhura Hospital Laboratory
	Karnali Academy of Health Science		Mahakali Hospital
		Lumbini	Bheri Hospital, Nepalgunj, Banke
Sudurpaschim	Seti Provincial Hospital	Lumbini	Bheri Hospital, Nepalgunj, Banke
	Mahakali Hospital		Rapti Academy of Health Science
	Kamalbazar Municipality PCR Lab	Karnali	Bheri Hospital
	Dadeldhura Hospital Laboratory		Surkhet Provincial Hospital
Lumbini	Rapti Academy of Health Science, Dang	Sudurpaschim	Seti Provincial Hospital
	Bheri Hospital		Dadeldhura Hospital Laboratory
	Lumbini Provincial Hospital		Mahakali Hospital
	Provincial Public Health Laboratory		Dadeldhura Hospital Laboratory
		Karnali	Surkhet Provincial Hospital

sample coordination and transfers based on the following strategies:

(1) Provincial Laboratory (*PL*): Each laboratory may only transfer its samples to its provincial laboratory. All provincial laboratories may be reached from all other public laboratories in that province within an 8-hour drive, except for the province of Sudurpaschim, where the driving time between Kamalbazar Municipality PCR Lab and the Seti Provincial Hospital in Dhangadi is close to 10 hours. Consequently, with this assignment strategy, Kamalbazar Municipality PCR Lab has no possibility to transfer samples.
(2) Cross-border provincial laboratory *PL-cross province*): Each laboratory may transfer samples only to all provincial hospitals within 8 hours of driving distance, even if that implies that transfers occur to the provincial hospital of another province. All laboratories can transfer to a provincial laboratory with this strategy.
(3) n Strategic Partner Laboratories (n *SP*): Each laboratory is assigned n strategic partners. When needed, they may contact the partner laboratory and send samples only in case the partner laboratory still has sufficient capacity to process these additional samples within the next period. The strategic partners are predetermined and fixed throughout the planning horizon. As strategic partners, we set those laboratories that received the largest number of transfers from a particular hospital during the unrestricted coordination simulation run.

The performance of these strategies for the nationwide cooperation amongst only public laboratories is depicted in Figure 6. As one can see, allowing for transfers to provincial hospitals across borders may significantly reduce the fraction of delayed samples from 21.4% without any transfers to 8.5% on a national level. Thereby, restricting transfers to the provincial hospital within the same province performs significantly worse, with 17.7% of the samples being delayed. In particular, in Karnali, Lumbini, Sudurpaschim, and Gandaki, the ability to transfer across provincial borders has a significant impact. However, sending samples to one other strategic partner laboratory outperforms that strategy in all provinces except Sudurpaschim. When laboratories cooperate with two predefined strategic partners, delays can be reduced to 0.4%. For three strategic partners, delays can be reduced to zero.

The performance of these strategies is furthermore evaluated when cooperation is taking place only within province boundaries. We distinguish between transfers between public and between public and private laboratories. The results are depicted in Figure 7. It is striking that even with two strategic partners, public or private, significant delays remain in the province of Sudurpaschim and Lumbini. In Lumbini and Koshi, including private partner laboratories may decrease the fraction of delayed samples. For example, in Lumbini, including private laboratories and the coordination strategy *2 SP* reduces delays from 7.7% to 4.7%.

From these experiments, we conclude that the cooperation of public laboratories across provincial borders bears the greatest potential. In particular, it outperforms the inclusion of private laboratories when cooperation is restricted on a province level. We conclude that enabling cooperation only between public laboratories is an adequate starting point for the coordination of test samples on a national level. Furthermore, it is unnecessary to allow cooperation between all pairs of laboratories and, therefore, to require a persistent flow of information from all stakeholders. Promising strategies for sample transfer are allowing for transfers to province hospitals within an 8-hour driving distance and defining one or two strategic partners with whom individual laboratories may cooperate. We will evaluate the performance of these strategies under varying

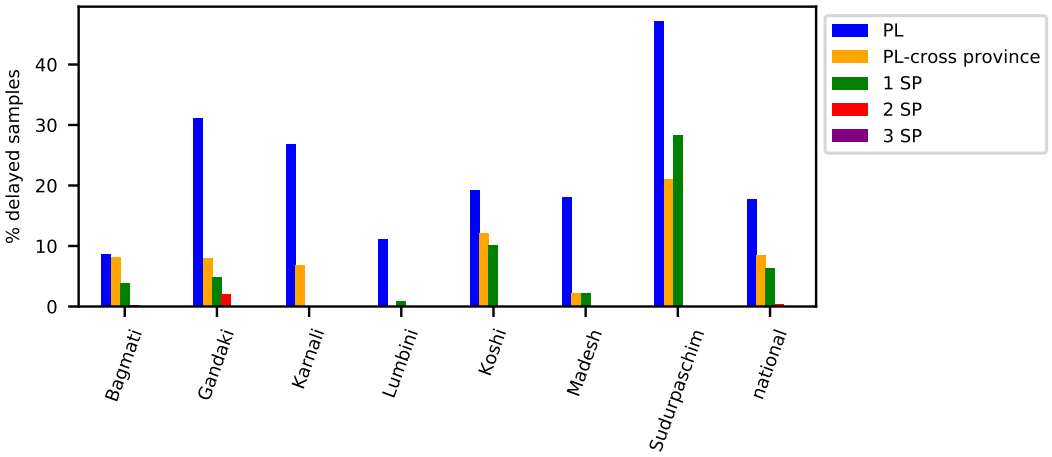
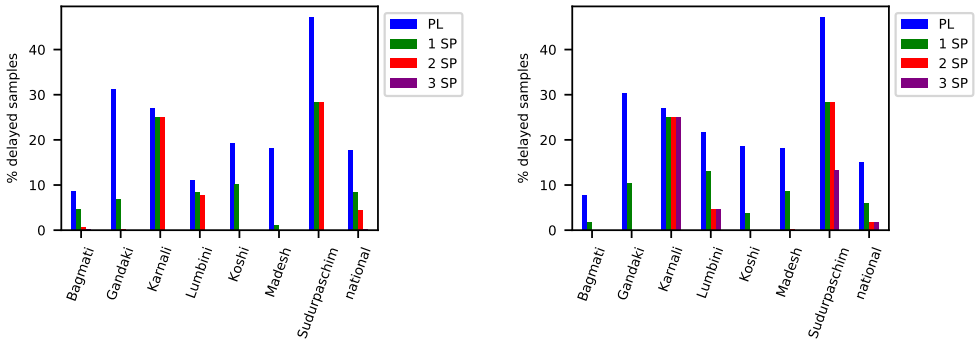


Figure 6. Fraction of delayed samples under different coordination strategies when only public laboratories cooperate across provinces



(a) Public

(b) Public & Private

Figure 7. Fraction of delayed samples under different coordination strategies within provinces

circumstances in the following.

5. Validation Experiments

In the following, we will investigate to which degree our observations hold under different sample volume and capacity estimates. For this purpose, we generate sequences of random scenarios in which certain characteristics of either the test sample volumes or the capacities are varied in a systematic way. The representative scenario described in Section 4.1 serves as a basis. We denote the incoming sample volumes at laboratory i in period t in the representative scenario with $\overline{d}_{it}$ and its processing capacity with $\overline{Cap}_{it}$.

Based on the results from the previous section, we reduce our analysis to only public laboratories that are allowed to cooperate with laboratories from different provinces as long as they are no further than an 8-hour drive away. Besides deriving upper and lower bounds for the fraction of delayed samples based on allowing no coordination or unrestricted coordination from an omniscient authority, we evaluate the performance of the simplified strategies *PL-cross province*, *1 SP*, and *2 SP*.

5.1. Increasing Fluctuations of Sample Volumes

The estimates for incoming sample volumes in the representative scenario are based on the 7-day moving averages for the reported sample throughputs of the individual laboratories. The large fluctuations in the reported data are artifacts of inconsistent reporting efforts, so they do not adequately represent fluctuations of sample volumes between consecutive days. Not only are the fluctuations in the reported data too extreme to mimic realistic fluctuations between workdays (with sometimes all samples of one week being reported on a single day), but they also differ significantly between individual laboratories, making it seem as if some laboratories suffered from extreme fluctuations while others remain largely unaffected. We, therefore, introduce artificial fluctuations of specified magnitude as described below.

Let Δ^f be a parameter specifying the degree to which samples fluctuate throughout the week. For a given value of Δ^f, we derive a sequence of $N = 30$ scenarios in which the incoming sample volumes at each laboratory are drawn from the following uniform distribution $U[(1 - \Delta^f)\overline{d}_{it}, (1 + \Delta^f)\overline{d}_{it}]$. We let Δ^f vary between 20% and 70%. For all generated scenarios, the total demand over the planning horizon, May 4th to July 1st, is approximately the same, with the coefficient of variation of the total demand volume across all generated scenarios at 0.6%. However, increasing Δ^f increases the differences between the sample volumes arriving at two consecutive days. In particular, Δ^f increases the probability that a laboratory has a huge spare capacity on one day and faces an overload of samples on the subsequent day.

The performance of different transfer strategies regarding the fraction of delayed samples and the fraction of delayed samples observed when no coordination is enforced is depicted in Figure 8. It shows the 95% confidence interval of the fraction of delayed samples observed across the 30 independently generated scenarios for each fluctuation level Δ^f. There are several noteworthy observations:

- Across all coordination strategies and all provinces, there is a clear trend that increasing fluctuations of incoming sample volumes increase the fraction of delayed samples. This does not come as a surprise, as we have already mentioned

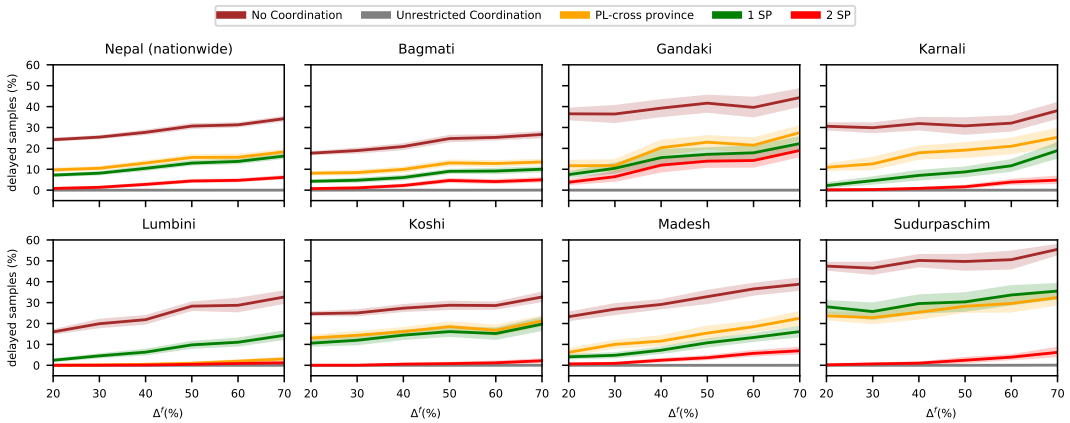


Figure 8. Performance of different strategies under different levels of fluctuations of test samples arriving at laboratories

that with increasing fluctuations, the probability of the incoming sample numbers exceeding the processing capacity of the laboratory on a particular day increases.

- Without any coordination, the fraction of delayed samples increases with increasing fluctuations in test sample volumes. On a national level, it increases from 24.1% for $\Delta^f = 20\%$ to 34.2% for $\Delta^f = 60\%$.
- The distribution of excess test numbers on individual laboratories only significantly affects smaller provinces, where there are fewer laboratories overall. Hence, the performance of an individual laboratory has a more substantial impact on the overall performance. In contrast, on a national level and in the province of Bagmati, the performance in terms of the fraction of delayed samples is very similar for a specific level of Δ^f and a specific coordination strategy. The range of the 95% confidence intervals does not exceed a range of 3%. This implies that results are rather independent of the actual distribution of test samples and fluctuations across individual laboratories.
- Coordination is an effective means to handling the increasing fluctuations. With unrestricted coordination, all delays can be avoided in all provinces.
- Regarding the performance of the simplified strategies, the picture is consistent across provinces. The ability to cooperate with two strategic partners performs best in all provinces and manages to keep the fraction of delayed samples below 10% in all provinces except Gandaki. Furthermore, in all provinces except Lumbini, cooperating with one strategic partner laboratory is the second-best alternative, performing slightly better than always sending samples to the nearest provincial laboratory. An exception to this rule is Lumbini, where cooperating with one strategic partner laboratory consistently performs better than only cooperating with provincial laboratories. This might indicate that it is worth expanding the capacity of the provincial laboratory in Lumbini.

As Table 6 shows, the ability to react flexibly to fluctuating sample volumes comes at the price of increased logistical handling efforts. The table displays the number of transfers issued by the different strategies - mean and standard deviation for the $N = 30$ scenarios - for $\Delta^f = 20\%$ and $\Delta^f = 60\%$. For both fluctuation levels, it is possible to avoid all delays when coordination is unrestricted. However, the number

of transfers required increases by approx. 150 transfers from 510 to 664 on average when Δ^f increases from 20% to 60%. Meanwhile, the fraction of transferred samples more than doubles from 4.0% to 8.8% on average. This implies that when fluctuations increase, not only the number of transfers required increases but also more samples need to be moved per transfer operation. With the simplified coordination strategies, total transfers decrease. As transfers are only initiated to avoid delay and may only be performed when the receiving laboratory has sufficient spare capacity, the reduced number of transfers directly translates into more delays. It shows that with the simplified strategies, one does not always manage to utilize all remaining capacity in the system.

In conclusion, we can say that highly fluctuating inflows of sample numbers may create a problem and should be avoided whenever possible. In particular, for active testing of health care personnel, this implies that one should try to even out the amount of testing done throughout the week. This means, e.g., that not every hospital tests personnel on Mondays and Thursdays but that different test days are assigned to different hospitals regarding the foreseeable, regular tests.

Table 6. Number of transfer operations required for different strategies for different fluctuation levels (mean (standard deviation))

	$\Delta^f = 20\%$			$\Delta^f = 60\%$		
	Unr. Coord.	PL-cr. prov.	2 SP	Unr. Coord.	PL-cr. prov.	2 SP
Bagmati	190.5 (12.7)	93.9 (6.3)	163.9 (9.2)	258.9 (19.5)	114.2 (12.1)	222.9 (12.1)
Gandaki	47.7 (6.0)	25.1 (2.9)	37.2 (4.8)	51.9 (10.7)	20.4 (4.6)	45.6 (9.3)
Karnali	25.4 (3.4)	10.2 (2.1)	18.8 (2.5)	25.7 (5.0)	12.5 (3.9)	22.0 (4.0)
Lumbini	46.1 (4.8)	40.8 (3.5)	50.7 (5.1)	65.0 (9.0)	48.5 (6.4)	68.2 (7.1)
Koshi	63.6 (5.1)	21.7 (4.5)	54.7 (4.2)	86.2 (11.8)	27.3 (5.7)	67.2 (5.6)
Madesh	82.4 (8.5)	35.2 (6.8)	72.1 (6.4)	115.0 (14.6)	40.7 (9.0)	99.0 (11.2)
Sudurpaschim	54.2 (4.5)	19.8 (2.2)	39.7 (3.5)	61.0 (8.1)	21.1 (4.3)	43.0 (5.5)
Nepal	**510.0 (19.4)**	**246.7 (15.7)**	**437.2 (12.9)**	**663.7 (26.0)**	**284.7 (29.6)**	**567.8 (20.4)**

5.2. Increased of Sample Volumes

Besides increasing fluctuations of test samples arriving between consecutive days, we are interested in seeing the degree to which increasing sample numbers affect the performance of the diagnostic system in place. Let Δ^i denote the parameter describing the relative increase in incoming sample volumes compared to the representative scenario discussed in Section 4.1. For $\Delta^i \in 2.5\%, \ldots, 48.5\%$ we generate $N = 30$ scenarios in which we draw incoming sample volumes from the following uniform distribution $d_{it} \sim U[0.8(1 + \Delta^i)\overline{d_{it}}, 1.2(1 + \Delta^i)\overline{d_{it}}]$. While the mean sample volume increases by Δ^i, the daily sample volumes fluctuate by $\pm 20\%$ around their mean in between different scenarios. The results are depicted in Figure 9 which allows for the following observations:

- Unsurprisingly, increasing sample volumes increases the fraction of delayed samples across all provinces and strategies.
- A look at the performance under unrestricted coordination gives insights regarding the general demand increase the system can handle from a capacity perspective. It shows that in most provinces and on a national level, an average of +20% of the samples could be processed without any resulting delays if they are efficiently distributed between individual laboratories. When no coordination takes place, this results in an increase of approx. 25% more of the samples being delayed.

- Gandaki or Lumbini can handle even greater increases in the overall sample volumes of up to 40%. However, particularly in Lumbini when samples increase by more than 20%, increased coordination is necessary to avoid delay, as one can see by the increasing difference in the performance of the two strategies *2 SP* and *PL-cross province*.
- Regarding simplified coordination strategies, one can observe that the ability to select between two strategic partner laboratories yields tremendous improvement over just one strategic partner laboratory. Meanwhile, cooperating with one strategic partner yields results comparable to cooperating only with the closest provincial laboratory. Both strategies yield significant improvement compared to no coordination at all.

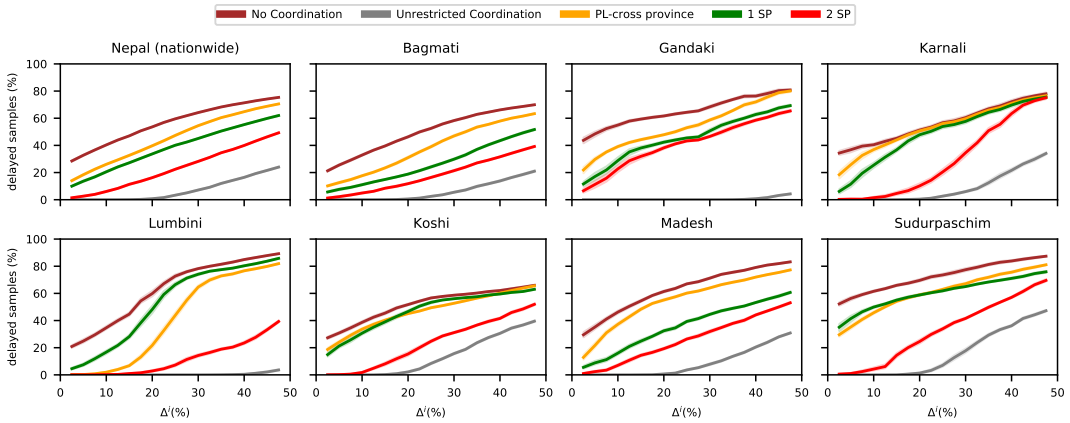


Figure 9. Performance of different strategies under increasing numbers of test samples arriving at laboratories

5.3. Capacity Estimation

The maximum processing capacities were estimated to lie at 80% of the maximum reported throughput of the individual capacities. Even though that number was validated, we explore how it affects our results regarding the performance of individual strategies. Therefore, in this subsection, we vary the capacity estimates homogeneously for all individual laboratories over all periods of time. In the upcoming subsection, we evaluate the result of dispersed capacity changes. Let Δ^c denote the fraction of the maximum reported throughputs, which we will take as a capacity estimate for the individual laboratories. For generating different scenarios, we vary Δ^c between 65% and 95%. Sample volumes are randomly drawn for $N = 30$ scenarios from the following uniform distribution: $d_{it} \sim U[0.8\overline{d_{it}}, 1.2\overline{d_{it}}]$.

Results can be found in Figure 10. The Figure primarily supports previous findings regarding the hierarchy in the performance of different coordination strategies. However, at the same time, it highlights that if effective coordination was in place, the overall capacities in the network could be reduced significantly while providing an equal level of service as was observed without coordinated transfers. For example, on a national level with a capacity estimate level of $\Delta^c = 80\%$ (as we also use in the baseline scenario), we observe an average of 24.2% of the sample being delayed across all scenarios when no coordination is possible. Meanwhile, for the same capacity level, that fraction of delayed samples reduces to 0.9% when we allow transfers to two strate-

gic partner laboratories. Meanwhile, for a capacity estimate level of $\Delta^c = 65\%$, with the same strategy of cooperating with two strategic partners, we observe an average of 20.2% of the samples being delayed. Thus, assuming that current capacity levels are at 80% of the reported maximum throughput. If we consistently applied the strategy to enforce cooperation with two strategic partner laboratories, we could reduce overall testing capacities by approximately 20% (1-65/80) and still outperform the current system. This would come at additional logistical costs. In the given example, ($\Delta^c = 65\%$, *2 SP*), an average of 842.0 individual transfer operations must be performed, averaging 14.6 daily transfers. On the other hand, even if current capacities were increased by 15%, such that $\Delta^c = 95\%$, we would still observe an average of 2.6% of delayed samples. Thus, even though the logistical costs associated with enabling the transfers are significant, the costs to sufficiently increase capacities at laboratories to make transfers unnecessary are likely much higher.

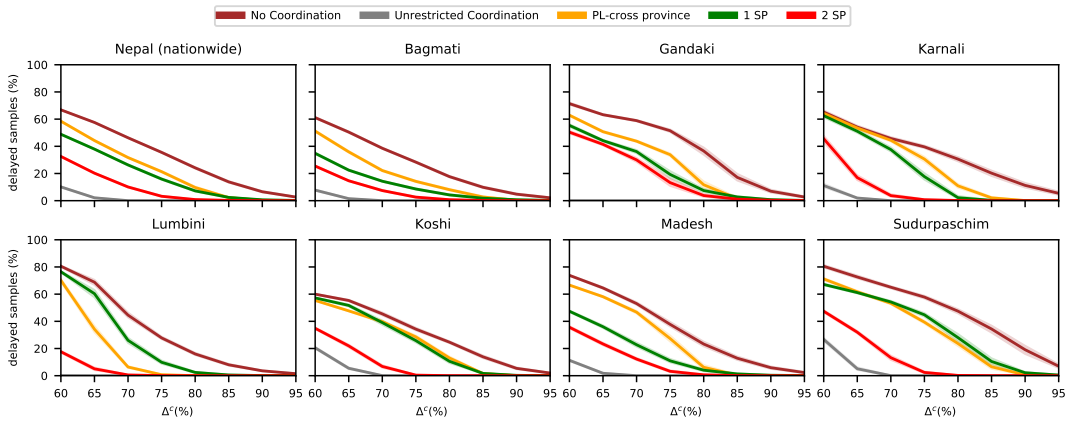


Figure 10. Performance of different strategies for different capacity levels at individual laboratories

5.4. Temporary Capacity Shortages

Besides homogeneous capacity increases and decreases, we evaluate the degree to which temporary capacity shortages at individual laboratories affect the performance of the diagnostic system in general, as well as the performance of coordinated sample transfers. According to officials, such shortages occur frequently due to shortages in materials such as reagents or due to staff falling sick. We define a shortage level Δ^s, determining the total capacity decrease per province. We generate a sequence of $N = 30$ scenarios for each level in which these shortages are randomly distributed across laboratories. If selected, a laboratory's capacity reduces to a level between 25% and 75% of the original capacity for 1 to 7 periods. Laboratories, shortage volumes, and duration are randomly selected until the accumulated shortages equal the defined overall shortage volume.

Results are depicted in Figure 11. Furthermore, it is not surprising that increasing shortage levels consistently lead to increased delays and have a more significant impact than homogeneous decreases of capacities. However, when unrestricted coordination is possible, the fraction of delayed samples starts to be greater than zero, approximately at 20% random shortages across all provinces. On a national level, with Δ^s =15% random shortages, the fraction of delayed samples averages 1.2%. Thereby, an omniscient

coordinating authority enabling unrestricted coordination significantly outperforms simplified coordination strategies, in particular in the province of Gandaki. However, the simplified strategies also yield consistent improvements.

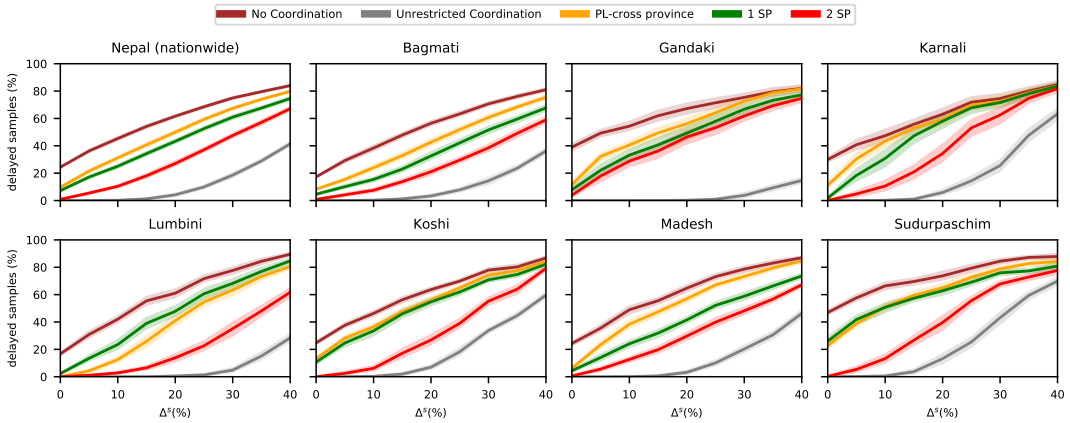


Figure 11. Performance of different strategies under different levels of random capacity shortages

6. Discussion

The analysis has shown that coordinated transfers of test samples bear a significant potential to improve the performance of the diagnostic network in Nepal. In the considered period of the Delta wave, May 4th to July 1st, 2021, the simulation shows a clear potential to reduce the fraction of samples not processed within the 24-hour target from 21.4% to 0%. This implies that Nepal's overall established processing capacities are sufficient even during high testing demand and that the experienced over-utilization of individual laboratories results from geographically imbalanced demand peaks.

The diagnostic network in Nepal is composed of public laboratories in all 7 provinces and private laboratories in 4 of the 7 provinces, most of the latter being located in the capital. As sample transfers between public and private laboratories and across provincial borders raise questions regarding the financing and thus require additional administrative processes, one focus point of this study was to investigate the potential of these forms of cooperation. The experimental results from May 4th to July 1st, 2021, clearly indicated a great potential in reducing waiting times for test results and enabling cooperation between public laboratories within the same province only. Additionally, extending cooperation between public laboratories across provincial borders has proven to be a more effective way to reduce waiting times than including private laboratories within the same province. While it is intuitive to think that including private laboratories can help to reduce the stress put on public laboratories during peak times, the study has shown that significant demand peaks often occur in laboratories in remote areas due to local outbreaks. As private, profit-oriented laboratories are located primarily in larger cities, they cannot help to relieve the stress in these areas. The improvement resulting from allowing transfers amongst public laboratories across provincial borders can be attributed primarily to the fact that this allowed transfers within reasonable distance for laboratories in remote areas in Sudurpaschim and Karnali, where road conditions result in long travel times even within the same province.

Therefore, moving forward, one should allow partnerships across provincial borders, not necessarily on a national level but between a limited number of laboratories in remote areas close to a provincial border.

Another focus point of our study regarded the degree to which coordination must be enabled to improve diagnostic performance effectively. While an omniscient authority initiating sample transfers, ad hoc outperformed all simplified coordination strategies. We must emphasize that simple strategies involving communication only between one or two laboratories significantly reduced the number of delayed samples. Identifying a limited number of strategic partners outperformed constant transfers only to the provincial laboratories throughout our experiments.

Lastly, we conducted a series of experiments exploring the degree to which coordinated sample transfers may help to increase the resilience of the diagnostic network, e.g., towards reductions in the overall capacity or random shortages. The results were clear. Even simple coordination strategies where each laboratory can only transfer samples to a single, predetermined partner significantly reduce the fraction of delayed samples under all considered scenarios throughout all provinces.

The present analysis comes with several limitations. Firstly, the model is highly simplified and focuses on analyzing whether the supply and demand of diagnostic capacity match on a strategic level. It thereby neglects many operational aspects that must be addressed before the results can be implemented. This includes, e.g., an accurate model of the sample arrival and transfer processes at the laboratory. In practice, rather than arriving once at the end of the day, samples arrive in batches throughout the day and enter the laboratory queue immediately. For a successful implementation of a sample transfer system, it is necessary to identify when and how to integrate the reporting of the incoming sample volumes and the initiation of the sample transfer process into the operational processes at the laboratory. Combining the presented model with a discrete-event simulation of the processes at individual laboratories can provide insights. Furthermore, the degree to which uncertainty is incorporated into the analysis assumes that capacity shortages resulting from staff sickness can be quantified precisely. In practice, obtaining accurate numbers on travel time, processing capacity, and prospective sample volumes is challenging, even for the same day. The simulation lacks mechanisms that model and mitigate the risks induced by such operational disruptions. Therefore, before implementing a central coordination system, further analysis that includes the operational processes at individual laboratories and effectively captures the uncertainties involved in the operational processes must be pursued.

Despite all these limitations, to the best of our knowledge, this is the first modeling approach investigating the effectiveness of different levels of centralized sample coordination mechanisms. Therefore, it gives essential insights into promising directions for further research and policymaking.

Disclaimer

This work represents the personal opinion of the authors and not that of the World Health Organization.

Declaration of interest

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7. Appendices

Appendix A. List of strategic partner laboratories

Table A1. Strategic partners laboratories when allowing transfers to once strategic partner across provincial borders, only considering public laboratories.

Origin laboratory	P*	Destination laboratory	P*
B.P. Koirala Memorial Cancer Hospital Laboratory	3	Madhyabindu Hospital	4
Shukraraj Tropical and Infectious Disease Hospital	3	National Public Health Laboratory, Teku	3
Siraha Hospital	2	Gajendra Narayan Singh Hospital, Rajbiraj, Sap...	2
Pokhara Academy of Health Science, Pokhara	4	B.P. Koirala Memorial Cancer Hospital Laboratory	3
Patan Hospital, Lalitpur	3	Kritipur Municipality-TU Biotech Corona Lab	3
Trishuli Hospital	3	Sahid Gangalal Hospital	3
Kalaiya Hospital	2	Gaur Hospital PCR Laboratory	2
Shree Birendra Hospital, Chhauni	3	National Public Health Laboratory, Teku	3
Rapti Academy of Health Science, Dang	5	Surkhet Provincial Hospital, Surkhet	6
Sahid Gangalal Hospital	3	Tribhuvan University Teaching Hospital (TUTH)	3
Tribhuvan University Teaching Hospital (TUTH)	3	Sahid Gangalal Hospital	3
Nepal APF Hospital, Balambu, Kathmandu	3	Shukraraj Tropical and Infectious Disease Hosp...	3
B. P. Koirala Institute of Health Sciences, Dharan	1	Provincial Public Health Laboratory, Biratnagar	1
Gaur Hospital PCR Laboratory	2	Kalaiya Hospital	2
Hetauda Hospital, Hetauda	3	Gaur Hospital PCR Laboratory	2
National Public Health Laboratory, Teku	3	Shukraraj Tropical and Infectious Disease Hosp...	3
Jaleshwor Hospital	2	Malangawa Hospital	2
Charikot Hospital	3	Provincial Public Health Laboratory, Dhulikhel	3
Malangawa Hospital	2	Gaur Hospital PCR Laboratory	2
Gajendra Narayan Singh Hospital, Rajbiraj, Saptari	2	Siraha Hospital	2
Vyas COVID - 19 PCR Laboratory, Tanahu	4	B.P. Koirala Memorial Cancer Hospital Laboratory	3
Provincial Public Health Laboratory, Pokhara	4	Pokhara Academy of Health Science, Pokhara	4
Bharatpur Hospital COVID-19 Diagnostic Lab	3	B.P. Koirala Memorial Cancer Hospital Laboratory	3
Dadeldhura Hospital Laboratory, Dadeldhura	7	Mahakali Hospital	7
Nepal Police Hospital Laboratory, Kathmandu	3	Sahid Gangalal Hospital	3
Narayani Hospital, Birgunj	2	Kalaiya Hospital	2
Kamalbazar Municipality PCR Lab	7	Dadeldhura Hospital Laboratory, Dadeldhura	7
Kritipur Municipality-TU Biotech Corona Lab	3	Shukraraj Tropical and Infectious Disease Hosp...	3
Paropakar Maternity and Women's Hospital	3	Shukraraj Tropical and Infectious Disease Hosp...	3
Koshi Hospital, Biratnagar	1	Provincial Public Health Laboratory, Biratnagar	1
Bhaktapur Hospital Lab	3	Civil Service Hospital	3
Madhyabindu Hospital	4	B.P. Koirala Memorial Cancer Hospital Laboratory	3
Provincial Public Health Laboratory, Janakpur	2	Jaleshwor Hospital	2
Provincial Public Health Laboratory, Dhulikhel	3	Bhaktapur Hospital Lab	3
Civil Service Hospital	3	National Public Health Laboratory, Teku	3
NAMS, Bir Hospital, Kathmandu	3	B.P. Koirala Memorial Cancer Hospital Laboratory	3
Provincial Public Health Laboratory, Rupandehi	5	Lumbini Provincial Hospital	5
Seti Provincial Hospital, Dhangadi	7	Mahakali Hospital	7
Dhankuta Hospital	1	B. P. Koirala Institute of Health Sciences, Dh...	1
Mahakali Hospital	7	Dadeldhura Hospital Laboratory, Dadeldhura	7
Mechi Hospital, Jhapa	1	B.P. Koirala Memorial Cancer Hospital Laboratory	3
Surkhet Provincial Hospital, Surkhet	6	Lumbini Provincial Hospital	5
Provincial Public Health Laboratory, Biratnagar	1	B. P. Koirala Institute of Health Sciences, Dh...	1
Dhaulagiri Hospital, Baglung	4	Provincial Public Health Laboratory, Pokhara	4
Lumbini Provincial Hospital	5	Provincial Public Health Laboratory, Rupandehi	5
Bheri Hospital, Nepalgunj, Banke	5	Surkhet Provincial Hospital, Surkhet	6
Karnali Academy of Health Science, Jumla	6	Surkhet Provincial Hospital, Surkhet	6

∗1: Koshi, 2: Madesh, 3:Bagmati, 4:Gandaki, 5:Lumbini, 6:Karnali, 7:Sudurpaschim