DOING A JIGSAW WHILE ON A TRAMPOLINE: DAMPING DOWN COVID-19 CYCLES OF INFECTION, ELIMINATION AND REINFECTION

Executive Summary

New Zealand has been in the eye of a storm, seeking to limit exposure to active sources of COVID-19, while continuing to function socially and economically. Extrapolating from the experiences in the rest of the world, we cannot ignore the possibility of several years of managing cycles of infection, elimination and reinfection from the COVID-19 pandemic.

Aside from personal behaviour changes, managing those cycles to date involves a test and trace approach for mitigating infection risks. This has been accompanied by regional or national lockdowns. To enable more certainty in when to start, stop or change the level or scope of lockdown. we need more knowledge of prospective population risks and increased system capacity for managing the various demands generated by surges in COVID-19 cases. Given that individual infection risks are quite different from population risks, they generate different information needs. Population-level perspectives can exploit the particular characteristics of COVID-19, with its 10 to 12-day pipeline of potentially identifiable infectiousness before symptoms are acted on. Individual level approaches are weak in this regard.

The impacts of lockdown are huge, in economic cost, personal wellbeing and public trust, while each new subtlety in lockdown form in New Zealand relies more on judgement than an advance in scientific observation and analysis. The processes which currently generate information at the start and end of lockdowns leave much to chance about the unmonitored population, and this is likely to generate external pressure to increase infection risks at that time. Lockdown costs could be avoided if a trustworthy containment strategy is put in place. This is increasingly important because of the accumulation of costs of lockdowns, including erosion of the public trust that underpins New Zealand's unique strengths in keeping infection at bay. The pressure to cease lockdowns reflects the range of information held by the public.

Whenever infection has returned, stabilising infection levels should become an immediate option in containing an infection outbreak, so that avoiding or shortening lockdowns becomes a practical choice. Currently the information that could determine prospective population risks is not collected from people during the stages of the infectiousness pipeline. This would become visible through random testing. The strategy of containment instead of lockdown would necessitate frequent gathering of information by random sampling of the population – meaning those chosen could be at any stage of the infection pipeline if they test positive. Such sampling would also provide prevalence estimates with known accuracy. Sewage sampling would complement this approach by giving an early indicator of possible infection in particular places or institutions.

Alongside this ability to predict and examine risks, strengthening the application of management sciences in the deployment of critical resources would increase our ability to deal with larger infection surges within the capability of the health services and the wider COVID-19 protection system. This would include early detection, more efficient contact tracing, robust statistics about the spread of the virus, protection of the vulnerable, sufficient PPE for health and care home workers, and controls over potential super-spreading events.

Applying operations research methods to supply chain management would make it possible to manage a greater than experienced surge in demand for testing and associated support. Containment does not replace test and trace, or the need for self-reporting, but it would ensure that

the information available throughout all stages of the COVID-19 pandemic in New Zealand was the most relevant for the decisions being made, and the best that accepted practices of observation and analysis could deliver. The projections made by epidemiological modelling would benefit from being able to be validated against current information about population prevalence.

Uncertainty about COVID-19 as a disease means that planning is akin to doing a jigsaw while on a trampoline. In the face of uncertainty about the capacity of our health system to deal with a larger breakout, or deliver a vaccine effectively, it is vital to strengthen the integration of systems that oversee the deployment of resources. Neither the understanding of prospective infection risks nor the integration of supply chains will advance without statistical methods and operations research expertise. As information about the COVID-19 virus is built up, the focus of observation studies and surge management priorities will likely change, as will an understanding of how personal behaviours need to evolve.

Government reviews and health system experts continue to argue for a health delivery infrastructure with the capability and capacity to respond to surges in need, and reports continue to be released on the consequences of the current system failings. But when operational systems and the information base are not aligned, this limits the capacity for on-the-spot adaptability when precautionary actions prove insufficient or unreliable. The findings of recent expert reviews are that investment in process improvement needs greater focus and resources. The fragmented nature of both the health system and the public sector means that institutional and regional solutions which function well may not do so when they have a common national purpose. We have seen this in the delivery of vaccines, and elements of the track and trace system.

The public legitimacy of actions involving COVID-19 is critical, and any perception of trial and error being the force for process improvement undermines public confidence at a time when it is the government's most vital resource. Even the small-scale border management now feasible has not been without failings, limiting confidence in moves to expand cross-border traffic. The capacity to progressively respond to surges in transmission of COVID-19, and be timely in doing so, should not be dependent on the extraordinary commitment of individuals at the front line. The visible cost of each lockdown in lost income, personal distress and loss of public trust indicates the scale of the opportunity cost of not putting in place operational systems and an information base that are aligned, scalable and founded in sound statistical science. The cost of further lockdowns would far overshadow the resources to achieve this.

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1. Introduction

When projections have indicated that domestic transmission of COVID-19 might exceed the capacity of health resources, the main policy response in New Zealand and many other countries has been some form of lockdown. New Zealanders must assume that domestic transmission will recur repeatedly. Rather than attempting to hold the virus at bay while waiting for a vaccine, it is vital to act now to improve our knowledge about COVID-19's prevalence and the health system's responsiveness.

Decisions about whether and when to move to lockdown require balancing various factors such as responsiveness of key processes, uncertainty about infection levels in the population at large, and the impacts on economic output, social wellbeing and public attitudes. Scientifically based tools exist that could increase what we know about these uncertainties and New Zealand must act to rapidly develop and apply them.

We already know that by the time someone tests positive for COVID-19 there is a significant chance that others will already be infected. However, uncertainty about this has led to the presumption that any outbreak could trigger a dramatic surge in the numbers infected which can only be managed by lockdown. There could be other options for responding if we had an early warning capability based on frequent measures of the prevalence of infection across the whole population, through statistical sampling. Conversely, the absence of information about the asymptomatic population may cause more frequent or longer lockdowns than are justifiable.

How statistical sciences make the difference

From what is known about the characteristics of COVID-19 there are clear benefits from lifting the capability to respond when vital resources must be rapidly redirected, by expanding early warning mechanisms. The impacts of lockdown level 4 in New Zealand and the recent experiences of Australia have heightened recognition of the economic and social risks from COVID-19.

Supply chain failings in health could have been anticipated by attention to the plethora of recent reviews and reports by health system experts on the current system failings (Ministerial Review Group (2009), Cook & Hughes (2010), Health and Disability System Review (2020), Wilson et al. (2020), PricewaterhouseCoopers (2020), Sonder & Ryan (2020)).

During the first outbreak of infection, the responsiveness of some government departments was exemplary, including the tax and income support agencies. However, there were multiple points of failure, most worryingly in the logistics infrastructure supporting health, food delivery and mail services. These functions are anchored in nationwide public and private infrastructure, which had its scalability tested by unprecedented surges in demand. In the paper we also discuss pockets of excellent practice that could beneficially influence thinking about systems and processes more generally.

The power of statistical and managerial sciences in improving the health logistics infrastructure has yet to be realised. Self-selection for testing and contact tracing cannot provide statistically trustworthy information about the possible prevalence of COVID-19 in the population. A systemised early warning capability is needed, such as through randomly selecting individuals for testing, and targeting a whole population group by sewage testing. Statistical supply chain management could transform the means to effectively manage and allocate resources that are scarce, have limited shelf life and could be needed at short notice anywhere in New Zealand. The New Zealand Blood Service is an effective role model in this regard. Areas that need transformation include testing capabilities, vaccines, personal protective equipment (PPE), and the delivery of food and other necessities in vulnerable communities. While a strong commitment to applying statistical methods to these issues will not remove the uncertainties of COVID-19, the opportunity cost from remaining ignorant of them increases with every lockdown.

Managing COVID-19 as a long-term condition

Beyond a certain level of infectiousness, the spread of COVID-19 within New Zealand will not be managed by the systems available, except by mandatory lockdown. Until 11 August 2020, New Zealanders had experienced 102 days of freedom. Since then most of the country has again faced some loss of normal community life. New Zealand has not experienced the same extent of public dissatisfaction over lockdowns seen in other countries and this may yet become significant.

The Treasury has estimated the cost of different levels of lockdowns, indicating that the net impact of a month at level 4 would see annual GDP reduce by approximately $9.6 billion. At level 3 the comparable loss would be approximately $6 billion (Treasury 2020). They estimate that alert levels 1 to 4 reduce output by 5–10%, 10–15%, 25% and 40% from normal, respectively. These estimates make it clear that the opportunity cost of lockdowns exceeds the cost of system changes on the scale proposed in this paper. Continuous adaptation, preventative monitoring, and innovation in operational practices are critical to raise the threshold for when lockdowns become necessary, and whenever they prevent or reduce the scope and scale of lockdown the payback will be high.

More strongly integrating the contributions of statistics, technology and medical sciences with operational processes would extend the scientific assessment and responses needed, given the uncertainty about future levels of infection within New Zealand. Reducing uncertainty about infection levels and transmission risks would facilitate decisions on the responses available to government.

The reviews and reports cited above highlighted how little prepared the health system was for the COVID-19 pandemic. At the start of the first outbreak the response was limited by weaknesses in contingent preparation, poorly integrated capabilities, and serious capacity constraints. Information systems were not ready (Cook & Gray, 2020). In view of the known areas of concern, and the ongoing need to be ready to respond to pandemic conditions, this paper makes the case for the implementation of national statistical systems and processes to monitor the responsiveness and effectiveness of the health system. It argues that these statistical systems should be an integral element of our health infrastructure (particularly the health logistics infrastructure) as they offer the capacity to position health supplies quickly and reliably where they are most needed. We describe a proactive supply chain management process that incorporates statistical tools to place stock.

This paper draws on information in the public domain, professional forums, interviews with practitioners and our own extensive experience in shaping, managing and monitoring complex systems. It is a response to the reports criticising aspects of the health system, and the huge pressures on the many people at the frontline of our defences against COVID-19 and who operate without the infrastructural support and information that could exist. We explain how statistical sciences can support Ministers and health officials in their decisions on preventing susceptibility to infection, responding to detected infection in symptomatic people and their contacts, and adaptation to emerging COVID-19 pathways.

The next section explores the uncertainties faced in the COVID-19 pandemic in more detail, followed by an examination of the current state of the public health infrastructure. Sections three to six discuss the tools available to prevent susceptibility to infection, respond to detected infection in symptomatic people and their contacts, and adapt to emerging COVID-19 pathways. The features of an integrated information system are then discussed. The final section sets out our conclusions on statistical elements of the structures, practices and methods essential for ensuring the integrity and cohesiveness of management, systems and processes of the health logistics infrastructure to protect New Zealanders from the COVID-19 pandemic.

2. Uncertainties faced in the COVID-19 pandemic

Uncertainty about COVID-19 as a disease means that planning is akin to doing a jigsaw while on a trampoline. The nature of COVID-19 has yet to be fully understood. Policy and strategy must evolve with the continually changing context and the uncertainties faced.

Risk, scientific uncertainty and the statistical properties of the COVID-19 virus

Risk management around the response to any pandemic must reflect its complex nature and dire consequences. The statistical properties of COVID-19 compared to other infections are critical in establishing the mix of monitoring and testing strategies that might increase the length of time that elimination and mitigation can continue without lockdown. Elimination is best defined as the absence of positive COVID-19 tests for the known life cycle of the infection.

The high uncertainty about the transmission mechanisms of COVID-19 is illustrated by recent understanding that transmission from asymptomatic people may be higher than previously thought. A recent United Kingdom report noted:

> *While those who have symptoms are more likely to test positive on nose and throat swabs than those without symptoms, out of those who have ever tested positive for COVID-19 on nose and throat swabs over the whole period of our study just 28% reported any evidence of symptoms around the time of their positive swab test.*
> (Office for National Statistics, August 2020).

There is more recent evidence that transmission may take place earlier in the infection cycle than previously assumed. There is clear age and ethnic variability in the mortality rate experienced overseas. Countries that reported early success in reaching zero new cases have had resurgences, as have New Zealand and Australia. Compounding matters, the risk of false negatives in tests for COVID-19 results in the possibility that domestic transmission will occur after people leave isolation. This makes the early detection of domestic transmission a critical priority.

Once one case of infection has been detected, there will most likely be a surge in the number detected. This reflects the breadth and speed of transmission that can go undetected before self-selected reporting identifies an outbreak of infection. Those who are infected but have yet to self-select for testing – usually because they have no symptoms – will only be detected if they are traced as a contact of a positive case. Because there is no scientific basis for retrospectively correlating those tested to the population, or population segment, it is impossible to estimate the overall prevalence of COVID-19. These infection counts are statistically meaningless in making inferences about the population at large, although being able to match those tested and their contacts with their National Health Index (NHI) number enables patterns in the clusters to be identified.

Emerging knowledge of the characteristics of COVID-19

There is little evidence that the reactive testing now done has adapted to knowledge that has developed about COVID-19 over the past six months. Undetected transmission will be influenced by access to health care, which will particularly affect Māori and Pacific communities (James *et al.*, 2020). Table 1 provides a summary of some research findings that should have influenced sampling methods and processes. This is not a comprehensive summary, but it includes characteristics which are judged to most affect the quality of either reactive or preventative monitoring. Some of the findings may have been expanded on since the initial literature review. These characteristics influence the nature of the preventative population monitoring approaches proposed below.

Table 1 Influence of research findings on statistical methods and processes

Research finding	Importance for surveillance, testing and process management
COVID-19 Infection path or "pipeline"	COVID-19 can be in the population for quite some time before an infected person believes that their symptoms justify seeking medical attention, or that they should attend a testing centre. Researchers have found that a typical incubation period is five to six days, and it may take double that time for an individual who is asymptomatic to obtain a test.
Asymptomatic cases and early infectiousness	Recent findings indicate that infected people are most infectious before they are symptomatic. One international survey suggests that one-third to one-half of transmissions occur from pre-symptomatic individuals. (Ferretti et al., 2020). The mean proportion was 48% for Singapore and 62% for Tianjin, China (Ganyani et al., 2020)
Super-spreading events	Two recent studies suggest that some 80% of secondary transmissions may have been caused by a small number of infectious individuals (Endo et al. (2020), Miller et al. (2020)). If reducing the infectiousness of potential superspreading events becomes a focus of intervention efforts, this could be taken into account in determining the capacity and support needed for managing surges in the need for testing, and in designing a process for the random sampling of people, perhaps targeting events that meet certain criteria. There is some information which suggests that indoors events carry a much higher risk of superspreading than outdoor ones.
Heterogeneity of infection	Recent UK results indicate that secondary transmission within households appears low – 68 out of a total of 71 positive tests were in different households. Most people who tested positive in this study did not pass it on to others within their household (Office for National Statistics, 2020).
Varying sensitivity, cost and responsiveness of COVID-19 tests	How testing methods interact with population sampling may affect their effectiveness (Ganz et al., 2020).
Variability of risk of infection of different roles	A UK study noted: "Compared with non-key workers, odds of swab-positivity were 7.7 (range 2.4–25) among care home (long-term care facilities) workers and 5.2 (range 2.9–9.3) among health care workers (Riley, 2020). Within any population, susceptibility can vary among individuals.

The population effects of recurrence of domestic transmission

There can be little doubt that people in New Zealand have had better experiences since the COVID-19 pandemic began than those in almost all other countries of the world. Ironically, this position was reached despite New Zealand being found deficient in preparation for a pandemic by the World

Health Organisation in 2017, while those then assessed as the best-prepared are now facing horrific situations (World Health Organisation, 2017). The experience has highlighted how difficult it is to predict the consequences of such disruptive events, and the need to remain conscious of the huge uncertainty that results from the way prediction models inherently mirror the past in much of their methodologies. Vigilance in personal behaviours can be subject to huge variations that raise the risk of resurgence.

Population and immigration uncertainty

Public acceptance of lockdowns and the need to modify behaviours and habits has generally been exemplary. A minority of those going through isolation have presented risks by leaving before their period is over. Other exceptions include illegal immigrants who may not wish to be identified as such in government systems, including health services, that might identify their status. People who live in remote areas or who lack access to digital technologies are another disconnected group.

Not everyone will agree to be tested (or later vaccinated) for COVID-19, and this is becoming a serious matter elsewhere. Refusals increase the uncertainty in tracing and voluntary testing, and support the importance of non-intrusive testing such as via sewage. When a vaccination becomes available, those who refuse it will remain as potential spreaders, as might visitors from countries with different vaccination experiences.

The global context has deteriorated since New Zealand went into lockdown level 4 some six months ago. Those seeking to enter New Zealand require both isolation and later accommodation. They add uncertainty and high volatility to the systems and processes for responding to these needs, and a heightened risk of community transmission.

Health, deprivation and social exclusion

To live with COVID-19, the health of populations and the economic capability of countries have become intertwined on a scale that goes beyond the design of health information systems, institutional and managerial capability, supply chains and connectivity. In pandemics of the past, Māori and Pacific communities have become disproportionately affected, which can have intergenerational effects. For these communities in particular, the effectiveness of public health interventions is critical. Methods of testing and the resources for protection need to be proportionate to their community impact, rather than being tied to the smaller populations in these communities – which is the basis of most health funding. In addition, given past experiences, there must be a sound understanding of how these communities differ in what they require to accept the trustworthiness of nationwide policies.

Key elements of social and family life have recovered from the first major lockdown, but the loss of many low-paid service jobs has damaged the economic position of many households, and the scale of this is likely to have long-term effects as accumulated capital cannot be maintained or is lost through inability to keep up mortgage, hire purchase or loan repayments. The high proportion of household income required for rent creates a risk as income falls and the chance of eviction increases. Each resurgence of community transmission further reduces the economic resilience of households, as another group loses income. Although major export flows remain strong and thus protect economic viability, the mix of jobs has changed radically with the loss of international tourists and fragility of much of the retail sector.

How bubbles are defined has had a hugely varying impact on households, families and whānau. Working mothers with young children experienced a significant increase in family time demands at lockdown level 4 compared to those with children 12 and older (Prickett *et al.,* 2020). Those with older children managed very well in most cases. About half of all New Zealanders experienced an economic loss during lockdown 4.

Even though the transmission of other infections has reduced significantly this year, the social determinants of health tell us that for children in poorer households the likelihood of debilitating lifelong conditions, such as rheumatic fever, will have increased. The delay in diagnosis and start on treatment pathways for some with treatable conditions will be life threatening. For example, there is concern that the deferral of cancer diagnosis and treatment could affect the life expectancy of some people. When the health services have reduced capacity for ongoing treatments for a period because of COVID-19 demands, there is an increasing volume of unmet demand for conditions that have been regarded as deferrable.

3. New Zealand's current health infrastructure

The State aims to provide a universal, open access public health service funded by taxpayers. An important foundation of this service is the funding of public health interventions, such as immunisation for infectious diseases. Health policy advice, monitoring of the population's state of health, and outcomes from public health interventions are the responsibility of the Ministry of Health. The structure of the health system has frontline delivery of public health being provided by public, private and not-for-profit organisations. The State funds, procures and provides frontline health services to deliver public health outcomes through 20 district health boards (DHBs) that are managed as if they were commercial entities. Public health funding is administered through the DHBs, with some earmarked for other agencies to provide services, such as immunisation and public health. In some instances, the responsibility for specific health initiatives is given to special purpose Crown agencies, an example is the New Zealand Blood Service.

What vaccine delivery tells about the health logistics infrastructure

That there is no rational organisational model behind the New Zealand health system lies behind its dysfunction and limited adaptability. The overall coordination of the public health service is based on a funder/ provider model using contracts for service. The Government, working through the Ministry of Health and The Treasury, sets the purchasing priorities and funding. The general principle is that Government appropriated funding is allocated to the DHBs based on population. Public health units (PHUs) operate within DHBs but are contracted directly by the Ministry of Health who fund them (responsibilities of the 12 PHUs nationwide include communicable disease control). The Pharmaceutical Management Agency (PHARMAC), New Zealand Health Partnership and Central Region Technical Advisory Services (TAS) are responsible for elements of purchasing and contract management of the supply of health-related products.

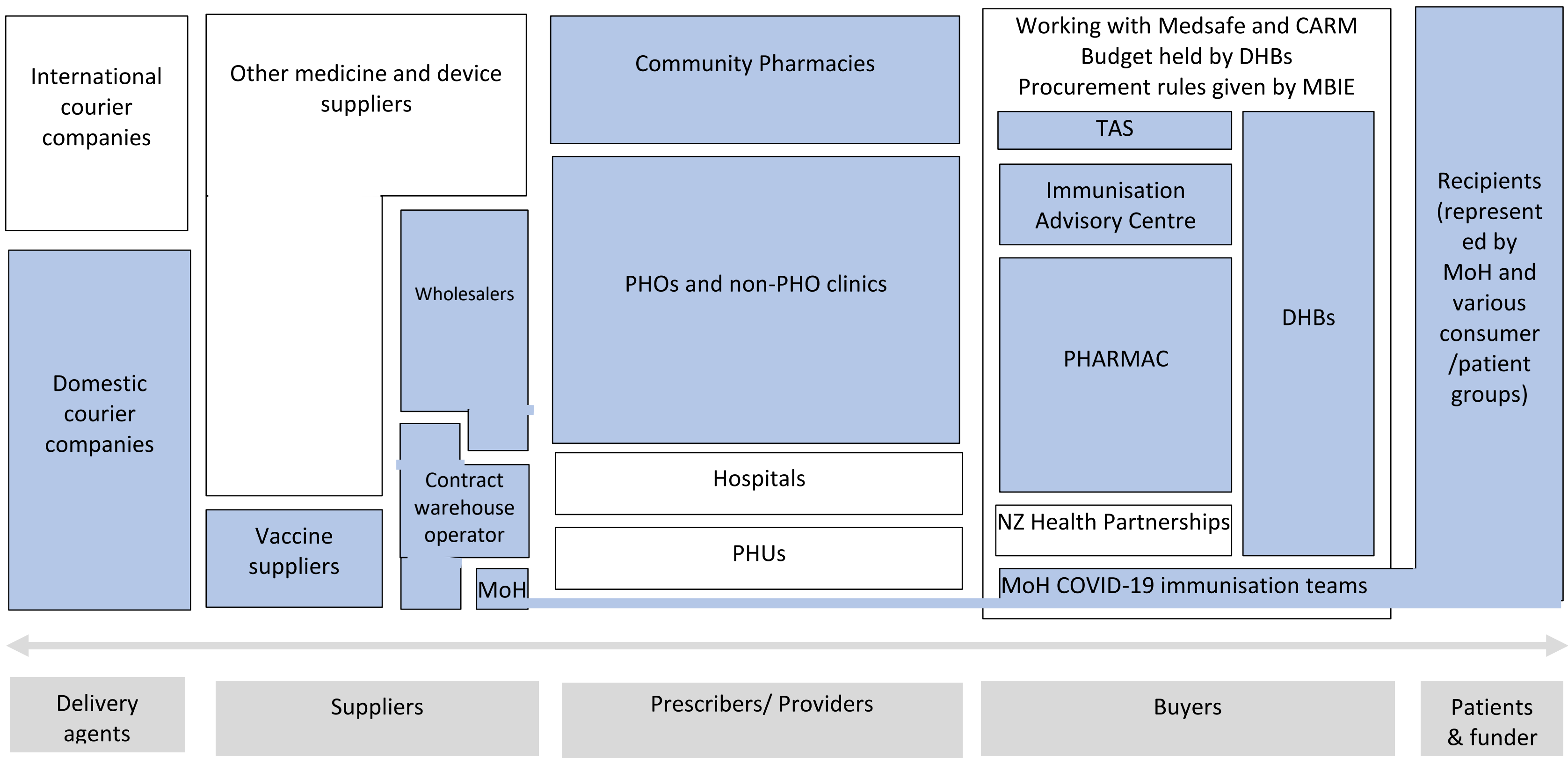
For example, PHARMAC is responsible for the purchase of medicines and devices, and schedule vaccines, but the gains from a single national purchaser are dissipated by the way that distribution channels are organised. Vaccinations are delivered by primary health organisations (PHOs) and some non-PHO clinics, community pharmacies and hospitals. These organisations are paid for each eligible person vaccinated. Records of people vaccinated are entered on the National Immunisation Register run by the Ministry of Health. Once supply contracts are in place, authorised delivery organisations deal directly with suppliers or the local contracted warehouse operator. For example, a clinic deals directly with the contract warehouse operator Health Care Logistics to order influenza vaccines. The supplier arranges delivery through a courier company.

Any supply chain failures for schedule vaccines are notified to the Immunisation Advisory Centre. Each PHU has an Immunisation/Cold Chain Coordination function. This function ensures the appropriate delivery, storage and administering of schedule vaccines within their geographic area. They also deal with any problems that might occur in the process. The integrity of the cold chain is audited by Medsafe.

For products distributed to patients by the DHB, each DHB has developed its own distribution arrangements, including requiring the patient to obtain the product from a community pharmacy.

Figure 1 illustrates the funder/provider and buyer/supplier machinery of government model as it applies to the medicines and devices value network. The diagram highlights the health supply value network for vaccines, which will later affect the distribution of a COVID-19 vaccine. The diagram also shows that that in response to the COVID-19 pandemic, the Ministry of Health is moving outside of this model by taking on additional roles. For example, for the COVID-19 vaccine, units have been recently established within the Ministry of Health to lead the work to identify suitable vaccines and oversee its purchase, and distribution, and these roles are a move away from the funder/provider model.

Figure 1 Immunisation value network (blue) in the context of the medicines and devices value network



Alternative mechanisms for supply chain coordination

Organisations use a range of coordination mechanisms each with quite different systems and processes to manage the distribution of products with limited shelf life. The variations are not simply levels of functional enhancement built on a generic foundation.

Push/pull coordination is used when a low degree of responsiveness is needed, for example in the distribution of medicines and devices produced for inventories that are drawn down by buyers. Stock is sold on a first-come first-served basis. Distributors of these products use “economic order quantity” to calculate the level and frequency of stock replenishment. For logistics management, little information is required – mainly whether the product is in stock and where to send an order. Failed deliveries are either replaced by the sender or through carrier insurance.

A variant of this is when the product is manufactured to a buyer’s specification, for example a vaccine for a specific strain of influenza. Once manufactured, the vaccine is placed in a contracted regional warehouse for distribution within a region. The warehouse operator is instructed where to send a specified quantity of vaccines to frontline delivery organisations. The warehouse operator packs the order (to specified cold chain standards) for delivery by a courier company. These deliveries can be tracked using scanned data from the courier company. This information is used to confirm that orders are dispatched and delivered to recipients as ordered. This process uses **pull/push coordination**, and stock levels and rate of drawdowns from the warehouse are used to monitor usage of the product and its remaining shelf life. The initial order quantity and the stock remaining in the warehouse affect the capacity to respond to unplanned surges in demand. Once stock is delivered to a frontline delivery organisation, the management and usage of the vaccines is their responsibility, and records are kept in their systems. This means there is no national overview on the volume of vaccines held.

Pull/pull coordination is on-demand delivery of products when and where they are required and enables the repositioning of stock as needed. This is used by the New Zealand Blood Service. Blood products are a scarce resource with limited shelf life. To ensure that it is used within its lifespan, product may need to be repositioned from one location to another. To achieve this level of sophistication in the supply chain the Blood Service has its own fleet of cold store vans and an information management system that monitors stock levels and product specifications at each stock location (usually a hospital). Compared to other coordination mechanisms, pull/pull coordination has the greatest level of responsiveness to place its scarce resource where it is most needed. Pull/pull coordination requires timely information, and clear communication to enable logistics management decisions that encompass the entire supply chain. These systems provide surge capability to distribute stock that must be rationed. Other supply chain coordination mechanisms cannot achieve this level of responsiveness, as illustrated by the recent failure of distribution of influenza vaccines (Martin, 2020). At the hight of the COVID-19 lockdown people were urged to get vaccinated for influenza. It is reported that “more than 1000 vaccines were lost – sent to the wrong city – and by the time they were found they were useless” (1 News, 2020). Similar problems were reported with PPE not getting to some frontline responders (Chumko, 2020).

After delivery problems with the push/pull model, the Ministry of Health’s response has become increasingly interventionist in the medicines and devices value network. Influenza vaccines are usually issued on a first-come first-served basis as it uses a pull/push coordination mechanism. During the first COVID-19 lockdown, the Ministry of Health intervened to prioritise the allocation of vaccines made by Health Care Logistics. Because of the limitations of a logistics system using pull/push coordination, this extra approval step, as would be expected, added 48 hours to the order time – previously 24 to 36 hours (PricewaterhouseCoopers, 2020). In these circumstances, pull/pull is more appropriate, and that would require the implementation of a new logistics and supply chain system and processes of the sort we have described.

The state of supporting information management

There needs to be certainty about the limits to system capacity with each return of domestic transmission. When a COVID-19 vaccine comes available, we must be prepared to distribute it to quickly bring community immunity. Pull/pull supply chain coordination is the most appropriate way to distribute stock in a pandemic. It requires monitoring the stock condition and quantity, and projected requirements at each location.

Figure 2 is a high-level depiction of the information flows and capabilities that support an efficient health logistics infrastructure, representing four key capabilities:

- operational knowhow, systems and processes to perform logistics actions
- ensuring that the infrastructure components are fit for purpose and ability to adapt to manage uncertainties
- risk mitigation to ensure plans are met, including anticipating where resources may be needed, and evolving plans as needs change
- financial management to ensure that best use is made of the allocated funding.

Organisations with these capabilities require supporting information flows (shown in Figure 2 as A, B, C, D, E, F, G). These allow effective and timely responses to changing conditions and the uncertainties of a pandemic.

Aside from information needed to distribute the product where it is expected to be required (B) and to find out whether it is used as anticipated (C), information is also needed on whether the intervention delivered the expected outcome (D). This is used in risk mitigation, particularly actions that become embedded in the delivery infrastructure through changes from continuous learning (F).

Information to assess the state of elimination and immunity (A) is vital in dealing with the uncertain trajectory of a pandemic. This is used to adapt operational capability (E). Infrastructure adaptations must be managed within financial constraints (G).

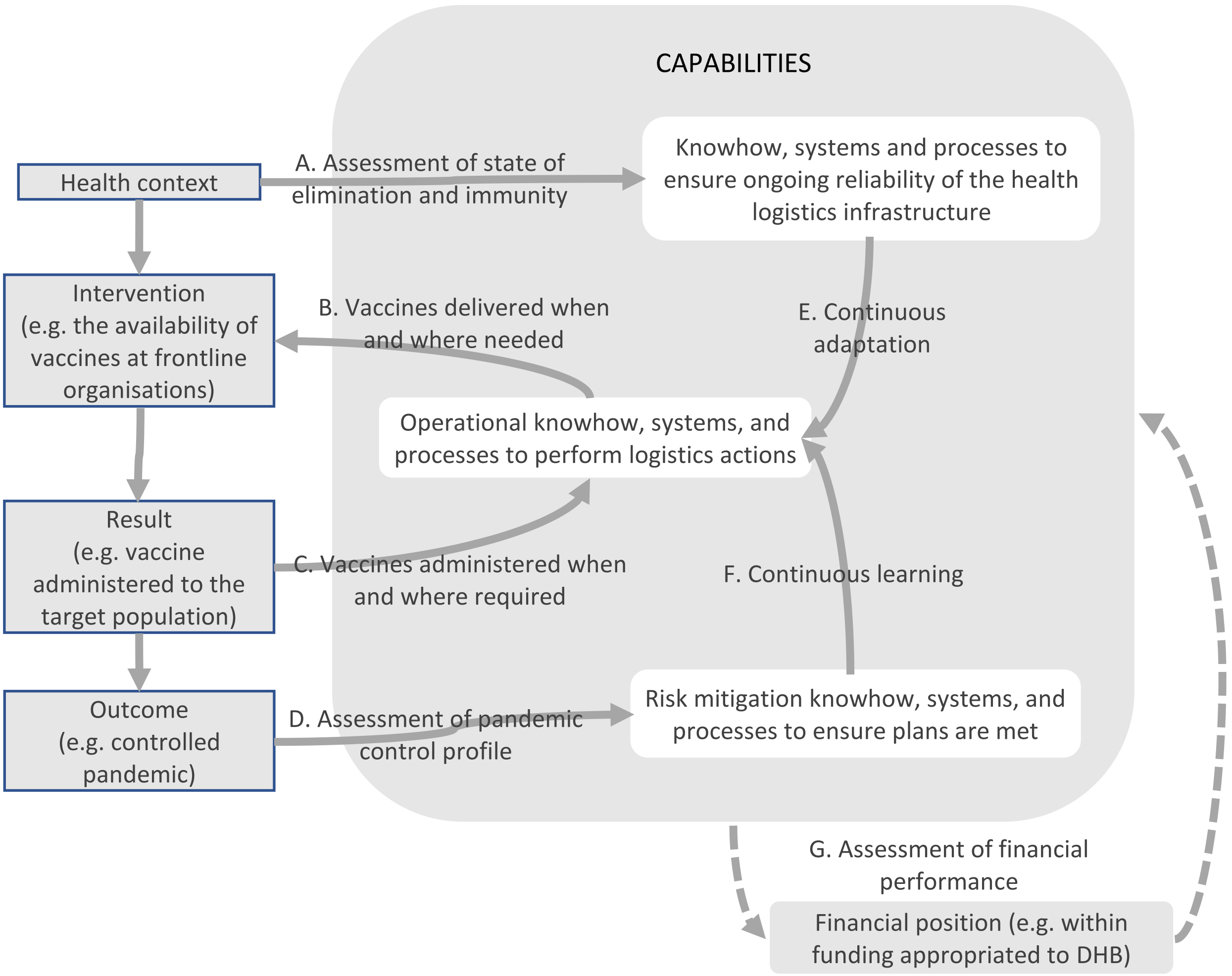
In New Zealand, a coherent strategic approach for sampling groups in the population has not evolved for monitoring options to assess the state of elimination and immunity (A) and emerging conditions (D). Components are non-existent, underdeveloped or unable to be fully applied when most needed.

Information flows A and D would use population-based statistical processes to estimate the state of COVID-19 cycles of infection, elimination and reinfection. The scope of this statistical information is broader than that usually associated with managing a supply chain, for four reasons:

1. Rapid response limits the spread of contagion.
2. There is a high degree of uncertainty on where and when an outbreak will occur.
3. The statistical properties of COVID-19, compared to other infections, requires a different mix of monitoring and testing strategies.
4. The cost of the alternative – a lockdown – is extremely high, and this warrants a coordinated national response.

These information flows are quite different to those that are currently in operation in the public health logistics infrastructure.

Figure 2 High-level depiction of the information flows and capabilities that support a health logistics infrastructure



Failures in links between operational competence in supply chain management to policy

The review of managed isolation and quarantine noted: "There were occasions when policy decisions were made with little understanding of the operational consequences." (Gibson *et al.*, 2020). The effectiveness of any operational activity is dependent on the viability and consistency of the underpinning policies. The rapid adaptation of policy by the Ministry of Health is at risk of being associated with weak adherence to process oversight. To avoid developing policy by trial and error, policy development must face challenges and testing that reflect the cost of implementation failure. It is vital that the high-pressure context of a pandemic does not preclude clarity in determining operating rules and monitoring process variation in real-time.

As with any situation where trial and error are a significant influence in driving change, there is a tendency to seek to address problems by finding new tools to add to the system, rather than comprehensively addressing the system as a whole. COVID-19 has generated a need to reassess the scale and form of contingent capacity that government and the public need to be willing to commit to the health system, and other services which become critical in a lockdown.

What of the pandemic plan now?

The inherent flaw in any attempt to plan for the COVID-19 pandemic was simply the absence of experience to draw on. With hindsight, the existing pandemic plan covered only a partial response to COVID-19.

The National Pandemic Plan 2017 states:

1. *As outlined in the National Health Emergency Plan 2015 all health emergency plans require ongoing testing through exercises to ensure they will be effective when activated.*
2. *Participation in inter-agency emergency related exercises will ensure all health emergency plans are well integrated. Integration is critical because most emergencies require some degree of inter-agency response.* (Ministry of Health, 2017)

Some five months after leaving level 4, neither review nor exercises have happened at the scale required to assure effective integration. The limited operational reviews that have been published (Verrall (2020), Allen & Clarke (2020), Auditor General (2020), Gibson et al. (2020)) contain invaluable information but are no substitute for an appropriately comprehensive evaluation. These reviews signal the need for change. The rapid lockdown response when COVID-19 re-emerged in the community indicates the cost of uncertainty about the scalability of tracing methods and the absence of any methods that use statistical sampling to track the prevalence of the virus in the population.

Rationing and allocative efficiency

Health services involve resources that are in short supply with a limited shelf life. They may have to be rationed based on need and allocated flexibly because of localised demand surges. Having multiple allocation processes that are not aligned results in delivery delays and product obsolescence/spoilage, reducing accessibility at critical times. There is a need to regularly reassess what is needed to reinforce management, systems and process integrity. For example, health, and other emergency and essential workers need reliable logistics processes that ensure access to appropriate PPE. To ensure the materials needed to fight future pandemics are obtained, there is a need for a systematic approach to monitoring global value chains and formalising regional alliances.

With the arrival of a vaccine for COVID-19, we will need an effective supply chain that can:

- distribute the products within the shelf life, and provide certainty of high quality
- cope with variations in participants with little notice
- match the likely location of the potential consumer base for a particular health need with accessible stocks.
- provide required information about product origin and supply to users and participants in the chain
- use patient/user feedback and ongoing monitoring to continuously adapt and improve processes.

A focus on allocative efficiency is vital for scarce health products, to provide the necessary certainty of access through rationing and delivery mechanisms based on the needs of patients/users. Allocative efficiency focuses on the whole stock portfolio in a way that minimises stock obsolescence and delivery time, while guaranteeing quality to support an effective public health intervention. For those scarce goods that are important to the COVID-19 pandemic (including testing kits, blood and blood products, vaccines and some PPE), a focus on cost efficiency at each separate stage will inevitably undermine the efficacy and effectiveness of access. This is because each stage in the delivery process is optimised by the lowest cost provider, who will seek to maximise their productivity, and may necessitate additional costs at later stages of the process.

At present, both PPE and vaccines are managed to maximise cost efficiency. This is at the expense of managing quality variations and stock obsolescence, as well as bringing uncertainty in delivery times for the final patients/users. In contrast, blood and blood products are managed to maximise allocative efficiency. The network centre retains full knowledge of each stock item until it is finally consumed, as well as information on the differences in the area-based distribution of all key consumer/patient segments, and the options for inter-regional transfer of the goods.

4. Preventing susceptibility to COVID-19 infection

Alternatives to national and regional lockdowns

New Zealand has been able to take advantage of characteristics which distinguish the country from others. An island nation can control arrivals and isolate them until it is demonstrated that they are not a source of infection. The public health system bears the full cost of testing people – even when they present with few of the known COVID-19 symptoms. In most cases income support is sufficient to provide for essential staff who have symptoms so they can stay home from work. Government actions have so far engendered a high degree of public trust, which can be expected to flow through to compliance with any restrictions in contact between people to cut off domestic transmission.

Without these strengths, we would be left to face COVID-19 with the same tools as other countries, whose response has involved prolonged lockdowns and isolation because of insufficient scalability of core contract tracing systems. In most countries there has been a strong dependence on the commitment of key workforces to "make do", despite system limits. How quickly the limits to the scalability tracing systems and testing capability could be reached with an outbreak was seen in Victoria, Australia.

In January 2020, New Zealand's contingent preparation for any form of pandemic did not provide those managing the COVID-19 response with a platform to direct and make operational the highly integrated response that had to involve everyone in the country. Up until early August 2020, New Zealand's COVID-19 strategy was unlike many countries in that we have been able to respond to it in two ways.

1. **Keeping COVID-19 at bay at the border** through systematised processes has enabled many organisations to function as normal in the absence of domestic transmission (which lasted for 102 days to 11 August 2020). This required preventing and mitigating exposure to COVID-19, while it has raged elsewhere. People could enter New Zealand from overseas, but the volume was limited to the capacity of managed isolation overseen by police and the military. There has been systematised testing of those who have contact with arrivals.
2. **Lockdown at various alert levels** was quickly instituted to contain community transmission before cases reached an uncontrollable level, and the process was repeated when the infection re-emerged. The "bubbles" concept provided a powerful means of managing the level of contact between people.

Two other options to lockdown are potentially available.

1. **Early detection of the transmission pathway and swift containment** without lockdown could be an option in certain conditions. It should be the response when domestic

transmission exists but is judged to be containable. It requires being highly adept at scaling up tracing, testing and treating.

2. **Immunity through vaccination or after infection.** The likelihood of either of these approaches to reduce the susceptibility to COVID-19 remains a distant hope but one which needs to be planned for now.

Each of these current and potentially available responses to COVID-19 should be regularly tested and independently validated to enable their continuous adaptation to new knowledge and experiences. The effectiveness at each stage of response is not certain, because we must assume that their form will keep changing because of the nature of COVID-19.

Rapid suppression and containment after detection of domestic transmission pathway

The earliest detection of changes in domestic transmission is the prime goal of testing randomly selected groups of the general population. The ability to generalise about groups in the population by such testing provides an earlier opportunity than any other means to decide whether it is possible to contain COVID-19 when there is domestic transmission without lockdown.

So far, tracing has only been carried out during some form of lockdown. In the first outbreak in March 2020 it was the nationwide level 4 lockdown, not tracing, that blocked all but a few transmission pathways. The second outbreak placed Auckland in level 3, and the rest of New Zealand in level 2. Being able to scale up tracing immediately on the emergence of domestic transmission is vital, as is confidence in the surveillance across at-risk groups.

To assess the risk of containment without moving to lockdown – so that a first response could be to heighten public awareness and expedite contact tracing – requires rapid understanding of the existence and scale of domestic transmission. For this to be possible by random sampling of selected groups in the population, it may need to be in association with forms of mass testing, such as via sewage, and supported by processes and practices by established statistical methods in statistical process assurance, statistical sampling and operations research. This is discussed in detail later in the paper.

Immunity

Reducing the susceptibility of the public to COVID-19 requires either previous infection, or a vaccine, and the capacity to obtain it by the Ministry of Health and then deliver it effectively. The effectiveness of a vaccine when it eventuates will depend on the situation in New Zealand at the time it is available, while access to a vaccine will depend on global demand. A strategy for nationwide delivery needs to be developed, as it is not feasible through simply changing existing practices and systems. Those who interact with people in isolation, and those who attend events with the potential for superspreading might be the top priority for vaccination. The ongoing uncertainty of global conditions will require intense monitoring before international visitors can arrive at the levels experienced in 2019.

Involuntary isolation

New arrivals to New Zealand are placed in controlled isolation under the supervision of the New Zealand Police supported by the military. Unauthorised departure from isolation is a crime. Practices have evolved that prevent those in isolation from being infected by new arrivals, and people working at isolation facilities must be tested regularly and strictly conform to rules that prevent transmission. Testing occurs twice while in isolation, but people are then free after leaving isolation to travel anywhere around New Zealand. Involuntary isolation in its present form is not scalable, and so serves well the purpose of isolating New Zealanders from the world at large. Because of the nature of global supply chains and the international connections of New Zealanders, it is not only the economic activity around tourism and education that requires the free flow of people into New Zealand. The absence of this puts a serious constraint on our medium-term economic prospects.

Personal behaviours

The encouragement for everyone to act as though infection is present has enabled the acceptance of sensible and practical ways for individuals to protect themselves. These actions have been a critical cornerstone of reducing susceptibility to COVID-19. None of the other actions discussed in this paper are a substitute for personal practices that aim to prevent domestic transmission of COVID-19, including bubbles, distancing, personal protection (masks, washing), symptom monitoring and test compliance. Seeking to be tested when showing at least one of the symptoms of COVID-19 is an important personal behaviour, as is isolating voluntarily when this occurs. However, the expectation that large numbers of people will voluntarily isolate must be supported by ensuring that food and medical supplies are readily available to those that do so. The need to continue these actions is regularly reinforced by the public health system, although after the first lockdowns ended, public commitment appeared to wane.

However, the effectiveness of an individual's adoption of appropriate personal practices can be undermined by the behaviour of others. Some people can be disaffected and seek to avoid engagement in actions required by government in protecting people's health. They may refuse to wear facemasks, practise social distancing or get vaccinated.

Organisational behaviours (aged care, factories, health services)

In places where there is a higher chance of encountering potential COVID-19 cases, or lower potential for controlling transmission than experienced by the public, institution-specific practices are necessary. This is particularly relevant for people who would be more likely to face complications or long-term effects from COVID-19 or who are at higher risk of dying.

A strategic approach to continuous adaptation for process assurance

The reports of Verrall (2020) Allen & Clarke (2020), Auditor General (2020) and the review by Gibson et al. (2020) examine parts of the COVID-19 response, but all four remain reactive rather than strategic. The recently published reports by the Contact Tracing Assurance Committee, monitoring progress with the recommendations in the Verrall report, are reactive as well (Contact Tracing Assurance Committee, 2020). These reports were all commissioned after problems were made known in the public domain. The issues investigated are not the ones which could most influence the capability of organisations in facing uncertainties when developing mitigating approaches. For example, statistical quality assurance methods have yet to play a part in such reviews. The priority given to and acceptance of reactive reports points to an absence of structure and systems oversight of the continuous adaptation processes now in place. The reports do not provide a basis for refining the options available to Ministers as their options are essentially limited to various levels of lockdown over large geographic areas. Diagram A in Figure 3 illustrates this method of managing the impact of COVID-19.

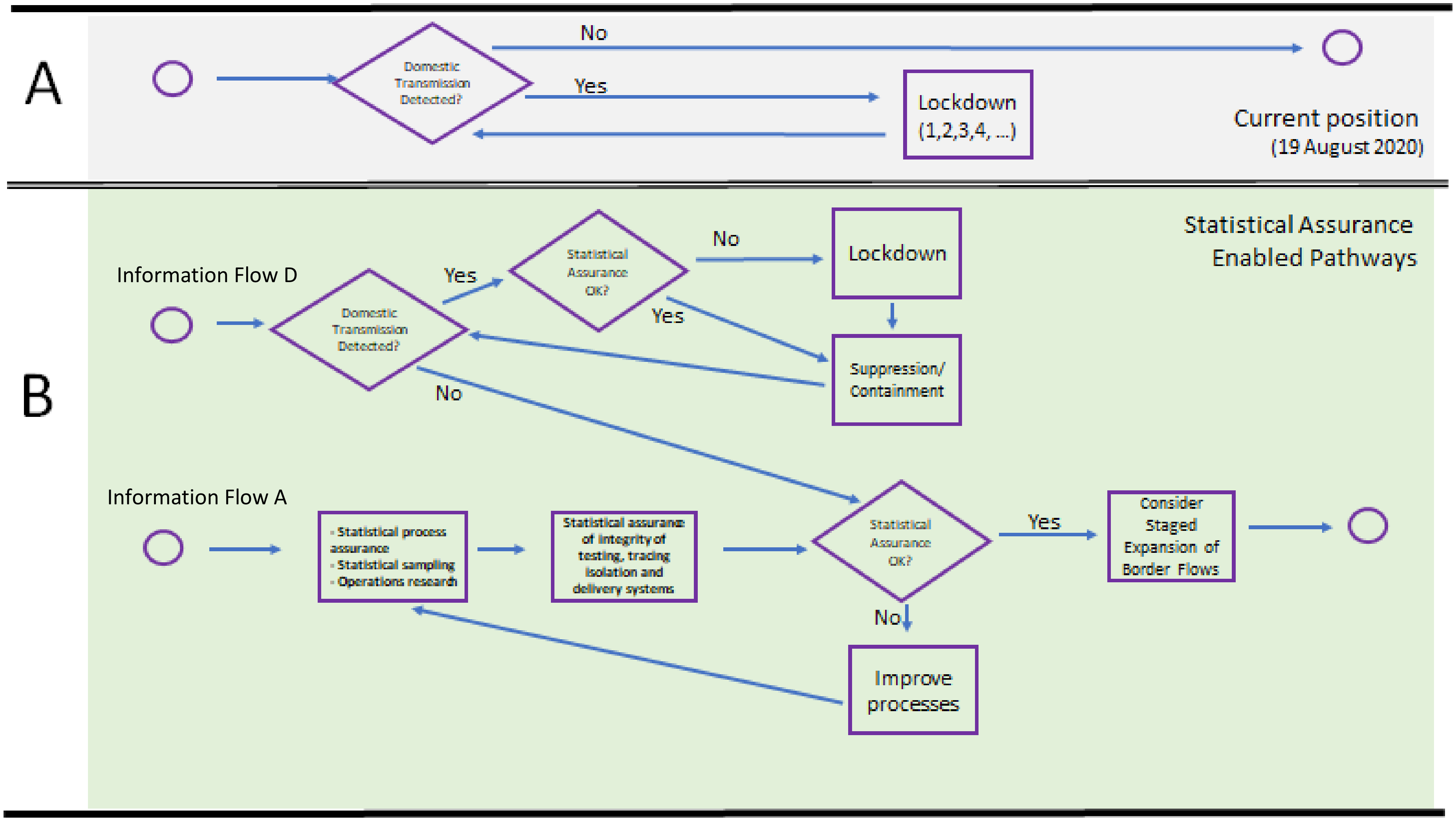
In a public statement of COVID-19 strategy, the Prime Minister noted:

> *There is an assumption in all of these scenarios that we know whether we have a contained outbreak or not. Where we don't have full information, we will take a precautionary approach, and scale back as needed, rather than run the risk of doing too little too late.*

This statement presupposes that it might be possible to recognise and quickly contain an outbreak. However, this capability does not currently exist, meaning that the "scale back" mentioned – some form of lockdown – is essentially the only option available.

Diagram B in Figure 3 illustrates an alternative, integrated approach to applying statistical methods and transforming systems that can deliver on that expectation. The two key statistical features are the monitoring of domestic transmission (information flow D), and the statistical assurance of the integrity of the process (flow A). Poor statistical assurance would mean a fallback to wide scale lockdowns to contain transmission (in effect defaulting to the process in Diagram A). A high level of assurance in the statistical information that indicates suppression or containment is critical.

Figure 3 Comparison between the current position and options enabled by statistical assurance



Adapting network organisation forms to oversee COVID-19 operations

In response to COVID-19, by pulling together the health system, the public service, police and military structures, New Zealand had the beginnings of a broad-based network organisation involving thousands of people. That is unusual for a public service and government whose organisational thinking is traditionally dominated by physical institutions. Since the initial level 4 lockdown, this networked structure has not evolved further, as noted in the recently published review (PricewaterhouseCoopers, 2020).

For this collaboration to be able to result in an effective network centre for protecting public health, the underlying logistics would use the information from statistical assurance of processes to operationally place resources where they are expected to have the greatest impact. It would also have the capability for continuous adaptation and learning, as in the uncertain context of a pandemic. Except for the New Zealand Blood Service, the concept of a network centre is at odds with a public sector management framework founded on policy/operational and funder/provider splits. A network organisation provides the vehicle for operational activities to reflect policy while managing the uncertainties of a continually changing context.

If the information that the network manages is proven faulty, then trust in other elements by those within the network is likely to diminish. The capability of any network organisation rests on it meeting clear quality standards reinforced by continuous adaptation. This necessitates:

- reliance on general adherence to a small set of common practices and standards;
- clarity of purpose at all levels that enables local discretion;
- a common system for information exchange in all directions;
- strong connection between science and practice; and
- real-time feedback mechanisms.

COVID-19 has challenged the knowledge base for network structures and contingent capability that are essential for the public health system to respond to a pandemic. At a time when government is reviewing the configuration of both health infrastructure and public services, plans established before the initial COVID-19 outbreak will most likely be found wanting. Although it will be difficult to predict how much additional protection would result from building a robust surge capacity into institutional sector structures, investments, and network forms, there is evidence of the high opportunity cost of not doing so - as seen in the reduction in GDP (Heatley, 2020). When the effectiveness of critical networks has been compromised by the drive for cost efficiency, the uncertainties of COVID-19 can mean that the consequence is to risk the quality of many people's lives.

Managing personal information

The capacity to share personal information rapidly in trustworthy ways is critical to minimise the spread of COVID-19, as well as maintaining the public's compliance in volunteering personal details when required. The systems currently available are far from best practice. They were found wanting during the small level of re-infection experienced and are unlikely to stand up to the demands of a full-scale outbreak. The practice by PHUs of storing information on spreadsheets and exchanging confidential information by sending spreadsheets as email attachments would not meet the standards set by public agencies such as Inland Revenue, Statistics and Customs. The practice fails to take advantage of the data management practices common elsewhere for several decades. A review on PHU testing capability noted:

> *While one PHU has a proprietary Public Health Information Management System (PHIMS), the others rely largely on Word and Excel, together with nationally available tools such as EpiSurv and REDCap. Cluster identification in this context has relied on largely manual approaches based on the accumulated case history knowledge of Medical Officers of Health (MOsH) and Public Health Nurses (PHNs). While this appears to have worked relatively well, it is not a reliable approach should case numbers increase substantially* (Allen & Clarke, 2020).

Competence in health-system-wide information management has yet to be demonstrated by PHUs and the Ministry of Health. The information management capability vital for a future health logistics network organisation and the management now of the COVID-19 pandemic will not emerge from the existing PHU systems in the required timeframe. Along with ensuring the quality of the information about people, there must be effective information management systems that store, retrieve and transmit that information. Without this, the alignment of the processes and connections of the health system in times of stress will be limited to what is possible through the capacity of people to apply extraordinary resourcefulness for extended periods in the areas that they know.

The current contribution of technological solutions for key processes

Apart from Inland Revenue and the Ministry of Social Development, those involved in managing COVID-19 related operations appear to have been faced with a paucity of whole-of-government technology solutions, and this has reduced the likelihood of building up either a health logistics network organisation, or a virtual network centre covering many institutions. What continues to occur, as exemplified by the COVID card (Checkpoint, 2020), is a plethora of disconnected proposals, meaning that the impact on reducing uncertainty and increasing the capacity to manage volatile supply chains cannot be compared because of the absence of an integrated view.

5. Reacting to detected infection in symptomatic people and their contacts

There are four main reactive monitoring processes currently in place:

1. individuals seeking a COVID-19 test, whether symptomatic or not.
2. tracing and testing the contacts of a positive case.
3. testing travellers held in isolation who after arriving overseas are required to spend two weeks in isolation. Testing occurs on days 3 and 12 of their two-week isolation.
4. periodic testing of some of the people whose role places them in contact with those who have COVID-19 or are in isolation. It is not known if these people are selected by any random process, and when that happens, they are discussed in section 6.

Self-selected testing

People are expected to identify possible COVID-19 symptoms and visit a testing station if they meet the thresholds established at any time by the Ministry of Health. These personal assessments of risk surge when COVID-19 is in the community. The huge fluctuations in the numbers who arrive for testing is unrelated to the actual risks that people face. It is not clear how knowledge about the changing characteristics of COVID-19 or about the nature of the population in any place influences the advice of the Ministry of Health – which is also prone to misinterpretation. The efficiency of this form of detection is very low. Even when some 30,000 were tested each day and the number of cases found in this way compared to track and tracing of potential cluster contacts was usually none, no inferences could be made about any other member of the population.

The testing process must be able to adapt rapidly to unexpected surges in demand. For example, during just one week in mid-August 2020 numbers tested increased from approximately 2,000 per day to nearly 30,000. On 29 August 2020, people in an area with a population of around 500,000 were accidentally advised on Facebook to get tested urgently, until the notice was rescinded as a communications error (NZ Herald, 2020). These huge fluctuations create lengthy queues that irritate the public and increase the risk that those who do need a test will not be able to get one.

Contact tracing and testing

When a community infection is first detected, in the following days a surge in positive cases is expected. As discussed earlier, this reflects how domestic transmission can go undetected because of the time it takes for an infected person to experience symptoms and get tested, followed by the contact tracing process. Those who are infected but have yet to self-select for testing – usually because they have no symptoms – will only be detected if they are traced as a contact of a positive case. The test and trace methods will change as infection rate rises (Imperial College, 2020). It is impossible to estimate with any confidence how testing by self-selection informs estimates of the prevalence of COVID-19 once transmission is under way and test and trace is in operation. Being able to match those tested and their contacts with their NHI number would enable patterns and clusters to be identified.

At the initial onset of COVID-19, the choices for government were stark, making lockdown essential. To protect people after that, the potential for containment was well reflected in the view stated by Verrall (2020):

> *Rapid case detection and contact tracing, combined with other basic public health measures, has over 90% efficacy against COVID-19 at the population level, making it as effective as many vaccines. This intervention is central to COVID-19 elimination in New Zealand*.

Verrall also noted:

> *An effective high-quality contact tracing system for Covid-19 will have the following characteristics:*
>
> - *Scalable – able to respond to exponential growth in case numbers.*
> - *Fast – contacts should be placed in isolation quickly.*
> - *Effective – contacts will adhere to the self-isolation direction and onwards transmission from contacts will be rare.*
> - *Equitable – high performance across age and ethnicity.*
> - *Acceptable – to contacts and PHUs.*
>
> *People's ability to quarantine and isolate effectively is a crucial component of a successful contact tracing system. 80% of cases need to be quarantined or isolated within 4 days of quarantine or isolation of index case to be confident the contact tracing system is effective.*

At each return of domestic transmission, the first notified case could have had the whole of their infectious period to infect others, whereas if some form of random sampling were in place, positive cases could be at any stage of the infection cycle. The rapid tracing and testing of the symptomatic positive cases identified by the initial contact is critical. The tracing process could involve a form of adaptive sampling, influencing the way that the initial contact provides further contacts who themselves continue this chain. In the case of an infection the aim is to test an increasing share of people who have become infected before they develop symptoms and engage with the health system.

We know that because the number of infected people can grow exponentially in the intervening period, the tracing system must be able to respond to unexpected surges in the number of the contacts of those who test positive. Those who have been contacts must be tested with the highest priority. If this chain of actions is set off rapidly, and minimal delay is achieved in all such cases, then each consequent transmission of infection from the first case will be detected earlier than the previous one, depending on the potential for secondary transmission. The indicator of “proportion of contacts with confirmed or suspected COVID-19 at time of tracing” should decline when the tracing process operates at full capacity (Verrall, 2020).

For an outbreak to be controlled, a point will eventually be reached where all those who test positive will have not been symptomatic or infectious. This rolling identification of contacts must be underpinned by support systems that can enable the rapid identification of super-spreading events which are potentially a source of multiple infections. The speed of taking swabs, as well as laboratory testing is critical in this. As more is understood about the transmission of COVID-19, the information gathered during an outbreak in the testing and tracing processes must be capable of rich analysis of spreading pathways. The capacity to handle surges in demand is essential.

Statistical methods are important in continuous adaptation of the key components of the tracing and testing system, and real-time analysis of the results, as well as managing the supply chains of the resources needed to meet rapid surges in demand. There is a need to identify the patterns in the contact outcomes that can signal the potential for containing an outbreak of domestic transmission without lockdown. Knowing for each infectious person, the number, proportion and type of their contacts that test positive can enable tracing priorities to be dynamically adjusted as the risk propensity of infected types of people or places becomes known. It will be also possible to determine whether the infection path is abating or not. Experience in New Zealand suggests that people in the same family or household are significant contacts that need testing, while recent results from the United Kingdom prevalence survey suggest otherwise (Office for National Statistics, 2020). By its very nature, adaptive sampling can respond to ethnic difference, but its contribution would be more effective if significant cultural communities had a part in the tracing activity (Meeking & Savage, 2020).

The expected reduction in transmission of COVID-19 by digital contact tracing systems assumes that a digital tracing system can further increase the effectiveness of manual contact tracing – when manual tracing is overwhelmed its effectiveness declines (Plank et al., 2020). There are limits to the contribution of digital contact tracing systems because a significant share of the population does not have easy access to these, and therefore will miss out on many of the initiatives being planned by government, as well as losing in-person services that they previously relied on. For many people in this position, their source of information and assistance will be networks including family or whānau, community organisations, schools, churches, marae, social media or workplaces.

Test and trace methods continue to be regarded as sufficient for New Zealand. This is despite the understanding being built up from experimental studies that the complexity of COVID-19 is such that contact tracing cannot provide the breadth, depth and reliability of information needed at critical times in infection cycles.

Testing travellers held in isolation

Those who have just arrived in New Zealand are being isolated in a manner which prevents further opportunities for transmission. Finding ways of expanding the number in isolation without increasing the risk of infection is critical, particularly if decisions are made to reactivate the education and tourism sectors. Given the nature of COVID-19, it is vital that the means of transmission from those in isolation are well known and that monitoring is consistently managed. An auditing capability is needed to ensure that quality standards are not sacrificed to meet invisible profit objectives.

6. Anticipatory methods to detect and forecast emerging COVID-19 pathways

Refining the targeting of contact restrictions will require much richer and more reliable knowledge of incidence patterns of COVID-19 than existing detection methods can provide. Random sampling methods provide the methodology for obtaining knowledge across the population, where individuals are to be tested. Practices such as wastewater sampling provide estimates at a group level as determined by an area or structure. The results of this may be used to determine whether surveying the population would enable further analysis that would provide more certainty of infection levels.

Preventative population monitoring

Without a surveillance system able to statistically measure change in infection levels at regular intervals and provide knowledge of the variation in risks of infection between groups, government has only crude means of determining the scale of actions that would contain a new outbreak of domestic transmission or inform the cessation of transmission. Non-statistical sampling of targeted groups in the population has been attempted, but it is apparent that unless there is a scientific basis for the mix of selection practices, it is unlikely that there could be any means of obtaining population information from those tested beyond satisfying individuals about their own condition.

Testing in a structured surveillance system will detect infectiousness before individuals become sufficiently symptomatic that they come to the attention of the health services. By being able to detect people who would otherwise come at a later date to the health services to be tested, the effective sample size of a statistical sample selected for this purpose to estimate the prevalence of infection in a group is increased. This also provides confidence to the public that whenever an infected person is found that the result can be placed in the context of the overall testing knowledge. For New Zealand, preventative population surveillance relevant to the risk related to each group will enable a wider range of public responses, including the continuation of more activities than in earlier lockdowns. It also would enable people to have some time to prepare for reduced contact, and more gradual tightening of restrictions. When domestic transmission is first detected or judged to be a significant risk, then instead of an immediate lockdown, government would have evidence that could indicate the likelihood that a surge in cases could be contained by testing and contact tracing, and reinforcing behavioural practices.

Applying statistical methods for systematising the monitoring of the population has been slow to develop in New Zealand, perhaps because risks of infection have been less tangible than elsewhere. Survey design experts have identified a variety of sample survey methods for preventative population monitoring (Steel (2020), Fisher & Trewin (2020), Haslett (2020)). The potential forms of statistical monitoring could be used are outlined below. The low rates of infection mean that the more immediate application of prevalence monitoring will be to determine an upper bound of infection even if the sample itself contains no infected people. It can also operate consistently over time, compared to voluntary screening where the fluctuation in the number testing may be misused as an indicator of prevalence. In this way, decisions about whether lockdown is required can be made with more certainty.

Epidemiological models

The focus of this paper is not on projecting infection pathways, but how to expand how the current situation is determined and enable a rapid response to any significant surge in transmission. Epidemiological models summarise what is unique to a particular infection outbreak and enable alternative infection pathways to be identified. Epidemiological models are critical for scenarios of the potential spread of infection from an outbreak and the potential for decline. The information behind epidemiological models would be enriched if the measures proposed in this paper are implemented, as timeliness of estimates of domestic transmission would be improved.

Sewage/ wastewater sampling

Testing that has the purpose of confirming that COVID-19 is not present can involve a high level of pooled samples, either gathered in a group as in sewage sampling, or in pooling groups of samples taken individually. New Zealand is not alone in seeking to do this; however, the situation is different in most of the countries with which we usually collaborate.

Wastewater surveillance by sewage testing provides the opportunity to test many groups in the population which are clustered around common sewage connections. Such groups could be determined by community or place, institution or building. Testing could be done as often as required. An ideal time for introducing sewage testing is when domestic transmission has been eliminated, as it could detect the return of any domestic transmission more quickly than other methods because of the large number of people tested. These tests can be done daily or even more often. They could also be carried out at isolation centres so as to monitor changes in infection levels. This testing will not identify which individuals carry the infection. Whenever infected individuals need to be identified in any group that provides a positive sewage test, there is the possibility that pooled testing methods can be used to reduce the number of tests needed to identify them (Haslett, 2020). Such testing could also be done at isolation centres to monitor changes in infection levels.

Household sampling

Continuous population surveys aim at estimating the level of COVID-19 infection in the population. One such survey has been operating since May 2020 by the United Kingdom Office for National Statistics. Proposals for New Zealand have been developed by the Statistical Advisory Group (SAG) to the Ministry of Health. Testing on a large scale is feasible now, and methodologies continue to evolve because of research in many countries. The scale and scope of such surveys would be determined by the level of confidence that authorities need to have in the measures of prevalence that would be obtained (quality of estimates). A household survey is one of the main means by which random sampling can add knowledge about the prevalence of COVID-19 (Cook & Gray, 2020). The United Kingdom continues to expand the range of information about the impact of COVID-19 on the population that could inform testing strategies and the substantive policy decisions about lockdowns, health services resourcing and special needs of highly at-risk populations (Office for National Statistics, 2020).

Random sampling of at-risk groups in the population

Groups in the population could be selected for random testing, if there is good reason to regard their risk of domestic transmission as higher than the population generally. Using the knowledge already gained of roles and institutions where people need to take a high level of care to avoid the risk of domestic transmission, it is possible to select places and groups for which random samples of people can be tested regularly. The size and frequency of such sampling would depend on the level and type of risk and the extent to which it appears manageable, the disparities in the degree of harm from COVID-19, and the potential for infection to spread. Even without statistical studies, at-risk roles should be identified. Another purpose of population risk group random sampling is to ensure that the opening of the border is accompanied by appropriate surveillance. As the number coming across the border increases, the risk of transmission will grow.

A key group at risk are the people who would be dealing with those in isolation (such as hotel workers) and who also have normal interactions with others who can move about freely in the general community. Risks to this group will increase as the flow across the border increases. These risks may be of more concern than the rare escapee.

7. The key elements of an integrated information system

Elements of statistical supply chain management

Statistical supply chain management is a form of pull/pull coordination that is proactive in ordering and placing stock where it is expected to be most needed. It is especially suited to the management of high value stock with a limited shelf life, such as vaccines. During a pandemic it must do this in the face of high uncertainty and within the health context. The health context gives recognition to the importance to the success of public health interventions through the licence given to Government to act by the public placing its trust. The public can withdraw trust for a wide range of reasons. In addition, there may be some groups, such as illegal immigrants, who may not wish to be connected with systems. There are also people who face barriers of social, geographic and technological exclusion. People in these situations can undermine the effectiveness of public health interventions, even when the interventions are supported by most of the population.

A distinguishing feature of statistical supply chain management is the use of statistical tools to monitor the presence of COVID-19, the response to the control intervention, and eventually elimination of the virus. These tools are quite different to those currently in use, which are reactive in their focus. To support proactive responses preventative population monitoring is required using tools such as sewage sampling, population risk group random sampling, household sampling and network tracing. To provide an on-going capability to respond to pandemics, these tools should form part of the national statistical system.

Information priorities for an integrated approach to supply chain management

For the COVID-19 pandemic, the scope of the information that is needed is broader than that usually associated with managing a traditional supply chain. There are three reasons for this:

1. A rapid response limits the spread of contagion.
2. There is a high degree of uncertainty on where and when another outbreak will occur.
3. The cost of the alternative – a lockdown – is extremely high.

Information flows needed for the management of the public health supply chain in the face of ongoing threat of COVID-19 cycles of infection, elimination and reinfection are quite different from those that are currently used in the public health system.

The interdependence of monitoring and screening strategies along with delivery capabilities will pose methodological challenges in the selection of measurement processes. These will be best met by survey design experts, epidemiologists, operations research practitioners, public health experts and medical practitioners collaborating at each phase of development. The monitoring system must meet these needs:

1. To detect the existence and possible scale and growth rate of domestic transmission before cases have sought testing through presenting to the health services with symptoms. This is also needed to determine the safety of any remaining domestic transmission, when removing lockdowns. In the same way, early warning is needed of when to reinstate containment actions, and when to stop them.
2. To monitor the accumulated experiences of different population groups with COVID-19, and their condition at any time so as to understand how the heterogeneity in the predisposition of people to infect and be infected influences how it is dispersed across the population.
3. To understand the differential impacts of COVID-19 on age groups, ethnicity, gender and health situation, and the longer-term consequences for their lives.
4. To understand the characteristics of COVID-19, and whether they are evolving.
5. To identify and trace the expected at-risk contacts of all who have the infection or are likely to have been a source of infection, to have them tested and isolated if positive. Super-spreading events are critical in the late stages of the epidemic when the virus is almost eradicated. This means that all aspects of the test and trace system must be robust in the face of surges in tracing numbers. Analysing the contacts of infected individuals could give an early signal of the likelihood of a super-spreading event affecting more people, as measured by the share of at-risk contacts who test positive.
6. To make use of knowledge of the relative risk in different environments of individuals becoming infected. Those who need to encounter people who may be infected with COVID-19 face risks of transmission depending on their role. Once the subgroup to be tested is identified, a random sampling scheme can be determined and systematically applied. Those who are known to be predisposed to COVID-19 seriously affecting their health, are another relevant subgroup for such testing, particularly when they are clustered, as in retirement homes and villages.
7. To assess the effectiveness of testing options, including assessing the continued effectiveness of the test and trace system in the face of COVID-19.

Nightingale assessment

The institution of a statistical supply chain management system of the type required to respond to the challenges of a pandemic requires a fundamental overhaul and replacement of the current distribution system. Given the reviews of the health system over the past decade, there is considerable agreement that the current system does not provide a suitable foundation from which to build improvements. The degree of unsuitability is shown by assessing the current system against our version of Florence Nightingale's (1854) three factors that destroy proper infection practices: ignorance, incapacity and useless rules. In the current context we would call these factors information, capability and system rigidity. This assessment is given in Table 2, based around factors that contribute to three fundamental priorities for Ministers in responding to change in the transmission of COVID-19:

1. preventing susceptibility to infection;
2. responding to detected infection in symptomatic people and their contacts; and
3. adapting to emerging COVID-19 pathways.

The degree to which the current system can prevent susceptibility to infection is assessed against five elements: immunisation, involuntary isolation, personal behaviours, organisational behaviours (aged care, factories, health services) and national and regional lockdown. Only immunisation is within the public health system. This is despite the expectation that the public health logistics infrastructure should have a large role in preventing susceptibility to infection. The effectiveness of a COVID-19 immunisation programme could be limited by current inadequacies in real-time information (PricewaterhouseCoopers, 2020). What emerges is that the public health sector has reserved for itself a role which does not include taking leadership in the systems and processes in preventing susceptibility to infection within society.

To adapt to emerging COVID-19 pathways we make the case for the use of tools that include epidemiological models, randomised samples of specially selected groups, random samples of the population, and special tests such as of sewage. Modelling is the only one of these tools currently in use (Binny, 2020), and this is not connected to the health logistics system. We argue that the place of these tools is to promote the adaptation of the public health response to COVID-19. What emerges from this analysis is a disjunct between this expectation and the actual, narrow reactive scope of the current public health system and its supporting logistics infrastructure.

Table 2 Florence Nightingale criteria applied to assess the ability of the public health logistics infrastructure to respond to COVID-19

Practices		Expectation of contribution to public legitimacy and degree to which met	Destroyers of proper infection practices		
Purpose	Instrument		Information	Capability	System Rigidity
Prevent susceptibility to infection	Immunisation	Expectation: Reliably placing vaccines where most needed. Finding: Moderate ability limited by inadequacies in real-time information.	Nature and availability of future vaccine and immunity from reinfection. Priority groups for vaccination and under what conditions.	Limited capability and unreliability of nationwide delivery system. Inability to reliably place stock where most needed.	Uncertainty of immunity leads to acceptance of risk situations by some groups. Buyer/supply model is not a suitable model for the distribution of vaccines.
	Involuntary isolation	Expectation: Managed risk-free entry of people from overseas into NZ communities. Finding: Operated outside of the public health system.	Tolerance of weak work practices for staff at quarantine facilities.	Unavailability of PPE and influenza vaccines when needed.	High accommodation and security fees become public issue. Without paid sick leave infected workers may be in workforce.
	Personal behaviours	Expectation: Greatly reduces susceptibility of all to COVID-19. Finding: Carried out outside of the public health system.	Disaffected groups. Discordant messages from public health authorities.	Disconnected communities.	Risk of negativity building momentum.
	Organisational behaviours (aged care, factories, health services)	Expectation: Ability of places of perceived high risk to function safely. Finding: Carried out outside of the public health system.	Failure to recognise relevance for activities and roles of COVID-19 risks.	Unavailability of PPE and influenza vaccines when needed. Inability to enforce practices.	Prevalence of infection higher in clusters of infected people does not influence system. Without paid sick leave infected workers may be in workforce.
	National & regional lockdown	Expectation: Susceptibility to COVID-19 limited to specific activities and roles that have to continue. Finding: Needs to be connected to health logistical system.	Sole response to uncertainty about prevalence and growth path of infection Sole response to uncertainty about infection spread/concentration	Sole response to inability to respond fast to demand surges. Provision of food and other necessities to vulnerable communities.	Huge long-term cost to social and economic wellbeing and business viability. Loss of trust in explaining trade-offs. Information inadequate to determine when to start/end lockdown when positive case numbers low.
Respond to detected infection in symptomatic people and their contacts	Self-selection for testing	Expectation: Enable quick diagnosis and isolation of people who test positive. Finding: Needs to be connected to health logistical system.	Reflects limited awareness of ways of measuring infectiousness beyond that of numbers tested. Limited relevance of performance measure – change in counts meaningless.	Affected by exaggerated surges from volatility of public sentiment. Generates unmanageable queues that raise distrust. Low-value use of testing resources and unjustifiable excessive pressure.	Likely to crowd out resources through lack of triage/ queue processes. Number tested is meaningless measure and risks public trust in wider system. Placebo effect for nearly all tested.

Practices		Expectation of contribution to public legitimacy and degree to which met	Destroyers of proper infection practices		
Purpose	Instrument		Information	Capability	System Rigidity
	Trace and test	Expectation: Enables control of small outbreaks through rapid testing of known contacts of infected. Also, signals effect to public that MoH is effective. Finding: Needs to be connected to health logistical system.	Misses out on benefits of adaptive sampling methods. Misses out on benefits of sewage/ wastewater sampling. "Gold standard" not adapting to increased knowledge. Dependent on compliance of groups when tracing required.	Limit to surge capacity. Delayed detection through limits to contact knowledge. Rigid performance measures not adapting to COVID-19 characteristics. Some asymptomatic cases tested through tracing.	Trace and test criteria not evolving with known COVID-19 characteristics. Reliance on trace and test exceeds its capability. Justification needed for confidence in test and trace as being as effective as vaccine as COVID-19 knowledge grows.
Adapt to emerging COVID-19 pathways	Epidemiological models	Expectation: Enable projections of prevalence of COVID-19. Finding: Could be connected to health logistical system.	Asymptomatic cases. Super-spreaders. Dominance of clusters.	Recency of observations. Relevance/rigidity of assumptions. Inherent tendency for exponential growth.	Limits to group disaggregation in projections. Requires infection to have been discovered for evidence needed to base projections. Projection uncertainty risk.
	Randomised samples of specially selected groups	Expectation: Infectiousness of whole sampled group estimated which is used to detect infectiousness of people before symptomatic and diagnosed. Finding: Not in use.	Power of method ignored/not understood. Failure to recognise relevance for activities and roles with COVID-19 risks.	Needs sampling expertise, frame & prior knowledge	Requires understanding of randomisation in inference. Undermined by exceptions to test rules when in border isolation.
	Random samples of the population	Expectation: Infectiousness of whole population group estimated, which is used to detects infectiousness of people before symptomatic and diagnosed. Finding: Not in use.	Prevalence measured before usual diagnosis undervalued. Power of method ignored/not understood.	Needs sampling expertise, frame & prior knowledge. Needs financial/system resources.	Requires understanding of randomisation in inference. Requires interviewer infrastructure to be redeployed.
	Special tests - sewage	Expectation: Enables frequent mass testing at community/institutional level, which is used to anticipate infectiousness before symptomatic and diagnosis. Finding: Not in use.	Methodology waiting to be fully tested.	Timely implementation overdue as priority too low.	Minimal once evaluated.

The importance of systematising information flows for aligning scientific expertise and operational capability

The dynamic nature of the COVID-19 pandemic necessitates agility in the digestion, reflection and formulation of responses to changes in risk, evidence and clinical options. Knowledge of the broader community context within which infectiousness must be controlled is essential, and if not measured directly it will continue to be inferred.

The huge consequences of process failure in COVID-19 operations demands clarity in determining operating rules that should involve systematised on-the-spot monitoring of process variations. This is at variance with a policy culture characterised by rapid adaptation of policy but weak adherence to process oversight. The tension from this must be openly confronted, so that as policies evolve, their operational practicality and continued relevance can be validated. With COVID-19, policy evaluation must be dynamic, and operations need to adapt continually. Even the most extraordinarily adaptable group of individuals will eventually wear out unless there is sufficient investment in the systematisation of processes and information flows. Given the uncertainties of COVID-19, the information sources need to span science-based expertise, including statistics, experience in operations, deep context knowledge and ensure a strong capacity to explain. Establishing a standing knowledge-sharing group to regularly review risks, management practices and systems, would make policy development and setting operational priorities more effective.

To date, people have been asked to take a test if they have some of the relevant symptoms, based on changing criteria. The rate of testing initiated in this way at any time is hugely influenced by public concern and messaging from authorities. Recent experience shows that the rate with which people will come forward is inherently unstable. During July 2020 the numbers volunteering fell considerably, then later reached nearly 30,000 per day. Although not one additional case is understood to have been found in this way, there was still no meaningful confidence that a zero result would represent the level of prevalence in the population. The perceived reliance on a testing system that involves such huge variations risks damaging public confidence through experiencing long queues and delayed receipt of results. Using simple statistical queueing models, operations staff could enable people to book online when there is a surge in demand and avoid consumers having to queue for periods of unknown duration.

Determine prevalence and detecting the onset of infection in groups

At any time, what is known about COVID-19 will determine how far the monitoring results and trust in the monitoring and testing systems adequately assess risk given the position with domestic transmission. The selection and design of monitoring processes should draw on both the knowledge available at the time about COVID-19, as well as the characteristics of the population that are correlated with its impact. These proposed means of estimating the level of COVID-19 in the population are well documented, and in place in other countries. The Statistical Advisory Group (SAG) to the Ministry of Health has provided discussion documents and advice on this (Haslett, 2020). There has been no published evaluation of options for systematised monitoring. Government reports on specific aspects of monitoring do not touch on how New Zealand compares with practice elsewhere (Contact Tracing Assurance Committee, 2020). Without a scientific basis for determining who is to be tested, then despite the very high levels of testing (up to 30,000 per day) at various times coming up with no positive cases it is impossible to make inferences about the prevalence of domestic transmission for anyone other than those seeking tests. Change in the number tested in this way does not indicate any degree of greater assurance.

Monitoring using random sampling methods will determine whether the prevalence of transmission is above the thresholds determined by the design and sample size. In this way, statistical prevalence sampling will detect groups in the population who could be at any stage from onset of infection to highly symptomatic. In the event of domestic transmission, statistically sound information can inform judgements about the implications for testing capability, health services and security, as well as the continued provision of products to maintain the wellbeing of the population. Some of these products will be in short supply, and their effective allocation will require a well-designed supply chain management system. The capability of the supply chains, as well as assessments of the current level of domestic transmission and its possible future course will determine the policy response at any time. We have explained in detail earlier what the monitoring system must achieve.

To be validated statistically, monitoring the population must be designed with specific purposes in mind. When the purpose is to understand the number of those who are at any stage of the COVID-19 infection path, or who may be asymptomatic, then statistical survey design will have many of the characteristics of regular government household surveys. The population that is to be sampled might be the total population, or a selected subgroup. Without population sampling, infection could simmer away undetected until some of those infected seek medical help. Ideally, responsiveness of the tracking system will eventually catch up with the newly infected before they were symptomatic and had infected anyone else. The likelihood of this will depend on several conditions being met, the most important being the continued relevance of the test criteria established for the Ministry of Health in April 2020 (Verrall, 2020).

Since April 2020 we have gained more knowledge from international studies of the nature of COVID-19. The experiences of Victoria, Australia, point to the criticality of the system responsiveness when a surge in need for tracing arises, while the recent cluster in Auckland highlights the importance of the adaptability of the tracing system to the communities associated with clusters (Meeking & Savage, 2020). The cessation of domestic transmission is assumed when no new cases are detected by tracing the contacts of infected individuals for two infection cycles – or 28 days. Population monitoring could be scaled up at such times so that the absence of transmission across the population could be determined earlier than this, with consequent savings in economic costs, smaller impact on social wellbeing and less risk of loss of public trust. This is not possible from the current testing system.

When to reserve testing resources for clinical needs and contact tracing will be an important factor in the scale of random sampling. There is a need to ensure that institutions that are supposedly under full lockdown such as care homes and prisons are sampled scientifically and included in the potential mix of monitored clusters. When a state of elimination or containment is reached, the form and scale of testing must reflect the huge opportunity cost of a return to lockdown.

8. Conclusion

COVID-19 monitoring in New Zealand is reactive and there is missed opportunity and cost to the public from the failure to use the statistical sciences of the study of populations. Various forms of preventative population monitoring are increasingly in use in other countries that are strongly anchored in statistical methods and are described in this paper. The alignment of screening strategies with the phases of economic recovery has been identified as a key benefit of a statistically sound monitoring strategy (Cook & Gray, 2020). A scientifically based monitoring system needs the collective knowledge of experts in statistical sampling, epidemiology, medical practice and public health.

In New Zealand our strong approach to responding to the COVID-19 pandemic has been highly effective at preventing the spread of comparatively low levels of infection, but this is at a cost that will become unsustainable if lockdowns are to be applied repeatedly. Reducing the risk of serial lockdowns in the continued absence of a vaccine places considerable reliance on the quality of monitoring strategies. The opportunity costs of any lockdown are many, and of such a magnitude that they heavily outweigh the costs of investing in systems that can respond to the rapid build-up of the high levels of infection common elsewhere. Beyond a certain level of infectiousness, the spread of COVID-19 cannot be mitigated through the best efforts of people without mandatory lockdown, because of the way that systems within health and other organisations currently operate.

In this paper we show what is needed to raise the threshold of infection that triggers lockdown. Given the continued transmission of COVID-19 at escalating levels elsewhere in the world, this should be put in place with some urgency. Managing an outbreak of domestic transmission so that its effects do not overwhelm health services requires a system that is capable of a degree of adaptability and scalability that is hard to achieve, and not possible by incremental change in the processes now in place. This requires increasing the surge capability of the system, along with investing in a strong early detection capability based on continually measuring the current level of infection by sampling people randomly.

Networked information management capability is central to systems that can meet these requirements, and the necessary communications networks that underly them are well established in New Zealand. We have identified information sources that could be invested in that would take advantage of the COVID-19 infection pipeline and so bring forward indications of change in the prevalence of infection. As well as influencing expectations for public behaviours, prospective infection levels need to be estimated in order to assess what other form of restrictions might be needed, and when they might be lifted or reimposed.

Maintaining public confidence must be a central focus throughout the management of the pandemic. Building confidence requires continual vigilance, regardless of whether active cases exist. It also requires preparation for the possibility – however remote – of infection at unprecedented levels. Each return of infection and consequent lockdown needs to be analysed as if it were the dress rehearsal for a bigger event. Some tasks will be needed again and again. They are:

1. Informing and managing the pandemic response so that its effects do not overwhelm the health system.
2. Having a sufficiently comprehensive set of information sources that can provide measures for government and the public that are consistent with the expert advice taken about whether restrictions can be gradually lifted or should be imposed again.
3. Enabling the highest possible return to everyday life in the immediate post-lockdown period by having a stronger capacity to detect and manage the re-emergence of COVID-19.
4. Managing the domestic economy in the absence of international visitors and adjusting to lower levels of demand for many services and lower levels of international trade, employment and investment.
5. Having the organisational capability, public trust and resources to enable community immunity from COVID-19 to occur without impediment whenever a vaccine becomes available.
6. Planning early for what is possible during the post-pandemic period after a vaccine becomes available but with a restructured open economy that has adjusted to the long-term shifts in domestic and international demand for products. This should include changed modes of interacting, and fiscal and income policies adapted to increasing the share of current resources dedicated to protecting the health and environment of people at a global level.

The published reviews do not present a picture of a coherent approach to countering the many unresolved issues through the lack of integrated systems across the health sector. There is insufficient review of existing practices in dealing with COVID-19, and system improvements can be made by having statistical sciences more embedded in all stages of decision-making, including operational, managerial, scientific and policy domains. There are lost opportunities from insufficient application of the wide-ranging statistical expertise available to managing COVID-19. The risk of losing the trust of the public needs to be actively managed by having the tools to generate confidence in processes.

Beyond a certain level of infectiousness, the spread of COVID-19 cannot be mitigated by the way resources available are currently managed, except by mandatory lockdown. Continuous adaptation and innovation in operational practices are critical for changing this, in particular:

- Using known statistical practices to design and build an effective early warning capability. For people in every distinct segment of the population, as determined by location, function and susceptibility to COVID-19, the probability of having been subject to a recent COVID-19 test must be known. Sewage testing is just one tool in this. Once domestic transmission exists, all phases of testing and tracing need to be able to scale up immediately, as a single system.
- Adopting the methods of statistical supply chain management. We do not currently have the means to effectively manage and allocate scarce resources with limited shelf life. This is particularly the case with testing capability, vaccines and PPE equipment. The Blood Service functions effectively as a role model in this regard.
- Applying established methods of quality assurance across the whole system protecting New Zealanders from COVID-19. The huge potential consequences of even minor process failure in these operations necessitates clarity in determining operating rules and monitoring process variation in real-time. This is at variance with a public policy culture with the rapid adaptation of policy but weak adherence to process oversight, and the tension from this must be openly confronted in such a fishbowl environment.

Many key health resources must be rationed, have a limited shelf life, and need to be allocated proactively because of localised demand surges. The multiple allocation and distribution processes in place in the public health sector results in delivery delays, product obsolescence and reduced accessibility to stock at critical times. At present, both PPE and vaccines are managed to maximise productive efficiency and minimise cost, which reduces the allocative efficiency of the system with such scarce resources.

In Scutari in the Crimea, Florence Nightingale established the beginnings of the science of epidemiology and advanced the use of statistical analysis in health as she developed the means to fight typhus, typhoid, cholera, scurvy and dysentery. She wrote

> *The three things which all but destroyed the army in Crimea were* ***ignorance, incapacity, and useless rules****; and the same thing will happen again, unless future regulations are framed more intelligently, and administered by better informed and more capable officers*. (Nightingale, 1854).

In measuring New Zealand's COVID-19 response against the three factors we have called **information, capability** and **system rigidity**, there can be no doubt that it deserves a very different endorsement than the Lady with the Lamp gave the British army some 175 years ago. However, the broad-based commitment to extraordinary efforts to manage COVID-19 are being applied in the face of a decade of documented concern about our fractionated health system. What does remain as relevant now as in 1854 for all complex systems, is the importance of systematised testing of knowledge, systems and rules. This sharpens our need to continually test the systems and information that are expected to support the best efforts of people and policy, as integrated components rather than elements of piecework. We must retain the utmost trust by people in the country's response to the extraordinary nature of the COVID-19 pandemic and the scale of its damage globally.

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