INVITED PAPER

A SIMULATION MODEL FOR COVID-19 PUBLIC HEALTH MANAGEMENT: DESIGN AND PRELIMINARY EVALUATION

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Abstract The COVID-19 pandemic has presented governments with challenges not only in relation to bio-medical understanding, medical treatment and health facility operations, but also the management of public health, public behaviour and the economy. In the area of public health management, discrete event simulation modelling is capable of providing considerable assistance to decision-makers. In April 2020, on the basis of publicly available information about the virus and its impacts, an analysis was undertaken of the needs of public health policy-makers, and a 16-state / 40-flow model was postulated. The model was revisited in December 2020, and experiences around the world applied in order to evaluate the model's apparent usefulness. This resulted in improved appreciation of its applicability and limitations, a revised model, and plans for further evaluation and application.

Keywords: discrete-event simulation, pandemic, public policy, DSS

University of Maribor Press

DOI https://doi.org/10.18690/978-961-286-485-9.1
ISBN 978-961-286-485-9

1 Introduction

From time to time, viral epidemics within individual countries threaten the health and lives of that country's inhabitants, and may wreak havoc on social and economic activities. Once the threat has passed, recovery may be quite brisk, provided that the country is sufficiently economically open. Global pandemics, on the other hand, harbour the potential for health impacts over large regions and potentially the whole world, and may have longer-term impacts on economic wellbeing because all countries' economies have been hampered and hence drivers of recovery are in short supply.

A century after 'The Maybe-Spanish Flu' at the end of World War I, the world was subjected to 'The Maybe-Chinese Coronavirus'. Naturally, ways were sought in which information technology (IT) could play a constructive role in the public response to the pandemic. Foreground needs existed in the area of prevention and treatment of the conditions that afflict patients. The particular need that is the focus of the present paper was for assistance in public health management, which seeks to slow the spread of the virus, protect particularly vulnerable sub-populations, ensure capacity to treat sufferers, and ultimately defeat the virus, while sustaining public confidence and achieving sufficiently high levels of compliance.

Emergency funding was provided to enable experiments with medical tools (e.g. for infection-testing, antibody-testing, symptom treatments, discovery of the modes of transmission, spread-containment mechanisms and vaccination) and with computing tools (e.g. for contact-detection, proximity-monitoring, contact-tracing, data management and decision support). As is to be expected of urgent, rapidly-performed experiments with available tools and the brisk conception and development of new tools, a great many projects were ineffective and short-lived. A few, however, delivered very considerable benefits to individuals, societies and economies.

The domain addressed by this paper is support for decision-making about public health policy. There is a worldwide need for contributions to public policy in the area. Yet IT's contributions have been at best mediocre. Data gathering, reporting and graphical presentation are helpful, but far from adequate assistance to decision-makers, and in any case data collection and analysis have been haphazard and often ill-informed. To constitute information, and to enable the people responsible for public health management to make decisions, data must have context. That context may be provided by each individual policy-maker's own mental model. However, major programmes of this nature involve many stakeholders with diverse perspectives. The context is therefore multi-dimensional, it features competition among values, and the conception of the problem-space needs to be shared rather than personal.

The most powerful form of context is provided by models that are shared, that impose some degree of formality on the problem-space, that are sufficiently graphic that all stakeholders can relate to them, and that have an associated terminology that is reasonably common among the stakeholders. Given such a model, it becomes much easier to identify data that would be valuable input to deliberations, to generate and evaluate alternative courses of action, and to assess both the potential and the actual impacts of interventions.

The focus of this article is on a particular form of modelling tool, commonly referred to as 'discrete-event simulation' (DES). DES modelling enables expression of a model that represents a set of COVID-19 states that individuals may pass through, the conditions that determine the paths they follow, and key characteristics of both the states and the transitions. Research was conducted whose purpose was to postulate a model, apply it, assess its efficacy and improve it, in order to support mind-experiments and conversations about the real world into which public policy-makers were injecting successive interventions and refinements of interventions. As the purpose was the creation of an artefact, the appropriate approach was design science.

A DES model is a socio-technical artefact as that term is used in design science (Niedermann & March 2012, Gregor & Hevner 2013, p.337). The process described by Peffers' Design Science Research Methodology (DSRM) commences with problem identification and definition of objectives, which are followed by design and development (Peffers et al. 2007). Peffers et al. distinguish two related phases towards the end of the design research approach. 'Demonstration' of the use of the artifact solves one or more instances of the problem (e.g. by means of experimentation, simulation or case study), whereas 'evaluation' involves more formal observation and measurement of the new artefact's effectiveness in addressing stated objectives. This research included Peffers phases of Problem Definition, Objectives Definition, Design and Expression, and a Demonstration step.

The paper commences by briefly summarising key features of the COVID-19 pandemic during the period March to December 2020. An outline is provided of the scope for modelling to assist, at various levels of investigation and decision-making. It is argued that discrete-event simulation modelling has a good fit to the needs of public health management. A model is presented which was devised in April 2020 on the basis of then-available information about the pandemic and government responses to it. Developments in the field during the following 8 months are identified, and their implications for that model are investigated. It is concluded that such a model can provide an effective contribution by IT to the decision processes of public health policy-makers.

2 The COVID-19 Pandemic

The new virus first came to public notice in the form of an epidemic in the Chinese city of Wuhan beginning in December 2019. Unsurprisingly, it took some time to be recognised and then accepted as a serious threat to public health. On 11 March 2020, based on rapid growth in detected case-numbers in northern Italy, Iran and South Korea, the World Health Organisation (WHO) declared a pandemic. By the end of March 2020, it had exploded in the USA, Spain, Germany and France, with rapid spread emergent in many other countries.

In most countries, there was an early peak of infections lasting 2-4 months with deaths following after a 1-3 week lag, then a lull, then 6-8 months later a 'second wave' in many cases worse than the first (Econ 2020). By the end of 2020, substantial second waves were infecting very large numbers of people and killing large numbers, with the cumulative (known) case-count worldwide past 80m and the death-count approaching 2m. On these measures, only two pandemics of the last century have been worse: the 'Spanish Flu' of 1918-20, and HIV/AIDS since 1980.

The cause was identified as a form of coronavirus, spread primarily by an infected person coughing or sneezing, or perhaps even speaking or breathing out, contaminated droplets (over a range of perhaps 1m), or possibly aerosols or droplet nuclei (very small droplets, over a range of perhaps 3-4m), or by direct contact with another person, or by contaminating 'fomites', i.e. objects and surfaces in the infectee's immediate environment (WHO 2020b).

Susceptibility appeared to be quite low under 10 years of age, increasing with age, and very high for those over 70. Impacts on individuals ranged from short-term, unpleasant but variable experiences, to very serious lung malfunction and death from that or consequential causes. Over time, it became apparent that there are small but significant numbers of people who suffer impacts for an extended period after the initial (predominantly pulmonary) impact of the virus (SWPRS 2020). However, most infectees are asymptomatic, decreasing the likelihood of detection and hence increasing the likelihood of spread.

A person with the virus may be infectious from 1-3 days before symptom onset, then for a further 1-2 weeks for asymptomatic persons, up to 3 weeks in mild to moderate cases, but much longer in severe cases (WHO 2020c). There were no known treatments for the virus itself. The proportion of hospitalised patients needing admission to Intensive Care Units (ICUs) ranged from 5% to 15%. In some regions, ICU capacity proved inadequate.

Mortality was very heavily skewed towards people over 70, with the likelihood of death much higher for those with bronchial and some other relevant or otherwise debilitating conditions. Employees in hospitals and aged care homes were at risk of high viral load, and high-quality hygiene and personal protective equipment (PPE) were essential. Despite precautions, many health care workers succumbed, in the USA about 3,000, 1% of the country's more than 300,000 deaths during 2020 (Gn 2020b).

The focus of public health actions was on prevention of spread, most urgently among those at greatest risk. The public health imperative is constrained by the limitations of enforcement powers and resources, and by conflict with freedoms of action and movement, and with economic management. In some jurisdictions, those challenges were exacerbated by a lack of political will. Countries adopted varying approaches to public health management, with highly varying senses of urgency, varying levels of compliance by the public, and highly varying case-counts, fatality-counts and fatality-rates (WOM 2020).

3 Modelling

IT was applied to the gathering and publication of data, partly to inform and entertain the public, but more critically to support policy-makers in their efforts to understand the phenomenon. This paper investigates the question as to whether the seeming absence of an 'enterprise model' of the undertaking, and of 'information architecture' and 'data models' to support it, have hampered the potential IT contribution, and hence whether return on investment in IT can be improved by applying insights from modelling theory and practice.

A model is a simplified representation of a real-world system, which reflects interdependence among the relevant entities, structures and processes. Real-world socio-economic systems are open, complex and highly inter-connected. Simplification necessarily involves limiting the scope of the model, by placing the focus on one sub-system or two or more closely-related sub-systems, at one particular level of abstraction, and by excluding some factors and using proxies for others (Gault et al. 1987). A model therefore cannot replicate the real-world system (von Bertalanffy 1968). However, if key factors are appropriately reflected, experimentation with a model can deliver insights. At the very least, experimentation can suggest what data might be the most valuable to collect. In addition, participation in the modelling process may enhance observers' understanding of the world, and assist in making decisions about actions to take.

During the first quarter of 2020, it became clear that COVID-19 had a high infection-rate and was life-threatening for some categories of people. As the epidemic in Wuhan developed into a pandemic, it became increasi8ngly apparent that decision support systems (DSS), and the modelling activities intrinsic to DSS (Sprague 1980, p.1), needed to be applied.

During the pandemic, epidemiological models of the SEIR(D) family were much-discussed. These treat the population as comprising Susceptible individuals (S – those able to contract the disease), Exposed individuals (E – those who have been infected but are not yet infectious), Infective individuals (I – those capable of transmitting the disease), Recovered individuals (R – those who have become immune), and possibly Dead individuals (D).

Generally, however, models in the SEIR(D) family lack details needed for public health management purposes: "These models have [provided] information about tipping points and inform[ed] policy decisions. But ... these models are not adequate for modelling the human behavioural aspects that are important in disease transmission and epidemic dynamics" (Siebers et al. 2010, p.206); and Schipper (2020) argued that modelling us during the pandemic, because "the current epidemic model is medical, and narrowly so" (p. 7).

This paper adopts the position that appropriate support by IS and IT for public-policy decision-makers in dynamic contexts like a pandemic depends on the application of appropriate modelling techniques. They need to be instrumentalist, with a social-engineering orientation. Such models depend on careful definition of the system scope, and the level of abstraction at which the system is being observed. Key requirements of public health management are the establishment and progressive adaptation of a model that clearly distinguishes start-point(s), states, transitions, and end-point(s), and that identifies key attributes of each individual passing through the model (e.g. age-range and relevant-prior-conditions), and supports experimentation with different distributions of those variables.

The following section postulates such a model. The adequacy of the model is then tested against the phenomena and interpretations of them reported during the following 8 months of 2020, and adaptations are proposed in an endeavour to improve the model's capacity to assist policy-makers.

4 Simulation Modelling for Public Health Management

This section first discusses particular needs that arose during the COVID-19 pandemic in 2020, then outlines the relevant form of modelling, and finally describes an application of it that is argued to be of benefit to policy-makers.

4.1 The Needs of Public Policy-Makers

The focus of public health management is "**population-based health protection and promotion**" (Novick & Morrow 2008, p.60), with efforts "**organized and directed to communities rather than to individuals**", and with the prevention and control of epidemics high on the priority-list (Novick & Mays 2008, p.3). Key functions and practices are (Novick & Morrow 2008, pp. 40-47) are assessment, policy development and assurance.

The target-area for modelling activities in public health management is accordingly the processes of the spread of the disease, and the purpose is to deliver insights to policy-makers regarding the shape that interventions may usefully take, and their likely contribution to containing that spread.

An important distinction is made in decision theory between **factors that are strategic or controllable and those that are environmental or uncontrollable** (Peterson 2009). A further distinction is necessary between directly-controllable factors and those that can only be indirectly influenced. For example, outputs include published government advice, formal declarations and laws, whereas outcomes comprise the acts of individuals, which are only influenced, not determined, by advice, declarations and laws. The extent to which public behaviour is compliant with the intentions of public health managers depends on controllable factors such as expression, channels of communication and timing, and on factors that are far less controllable, such as attitudes to authority, perceptions of the health threat, and prior experience of government actions.

Two of the key weapons in fighting epidemics are **quarantine and isolation**. The term 'quarantine' applies to people who have been, or are suspected to have been, exposed to an infectious disease, but who are not at that stage known to be infected. The term 'isolation', on the other hand, is applied to people known to be infected. However, supervision of suspect-quarantine and infectee-isolation may be dependent on inadequately-trained staff, contractors or military personnel. Travel restrictions are difficult to police. Records of attendance at venues are maintained by individuals and venue-operators, and assurance of data quality and data-compatibility is challenging. The implementation of border restrictions may be haphazard where multiple agencies are involved.

Public health activities inherently involve a very broad range of stakeholders, and great **diversity among perspectives and values** spanning the social, economic and psychological dimensions. As a result, decisions are actively contested, and the decision-making processes complex and at best only modestly well-structured. The Vroom-Yetton-Jago Decision Model identifies five decision-making implementation styles (Vroom & Yetton 1973, Vroom & Jago 1988). For decisions that have significant impact and require input and 'buy-in' from many participants, the relevant two of the five are consultative (group-based but leader-decided) and collaborative (group-based and group-decided).

Because many stakeholders are involved, policy-makers are confronted by diverse views and a rich choice of experts, of approaches to models, of assumptions inherent within them, and hence of the findings presented by the modellers. For consultative and collaborative processes to be effective, participants need to have a shared understanding of the relevant domain and of the terminology used to describe it.

Models can contribute to that understanding by reflecting the key features of real-world systems that policy-makers seek to influence. Further, because pandemics develop in unpredictable ways, and new information and insights become available, policy-makers' appreciation of the context is adaptive. It is therefore crucial that policy-makers develop a degree of clarity about the context in which they are working, communicate that to modellers, and update modellers on changes in their perceptions of the relevant systems.

The most effective way in which modellers can contribute is to start with an appreciation of the relevant domain, to become familiar with the policy-makers' initial mental models, and to be sufficiently 'embedded' to detect changes in their thinking. Further, modellers must convey enough information about their purposes, their assumptions, the capabilities and limitations of their methods, the nature, quality and quantum of the data that they are using, and the extent to which it has and has not been feasible to test findings against the real world. Without great care, there is a high probability of misunderstandings, and of policy-makers being misled.

The following sub-section considers how a particular form of modelling can be used to address these needs.

4.2 The Modelling Method

Multiple forms of modelling exist. At the strategic level, for example, system dynamics is appropriate (Brailsford & Hilton 2000, Brailsford et al. 2014). A particular modelling approach that matches well to the needs of public health management during a pandemic is discrete-event simulation (DES) (Allen et al.

2015). DES modelling involves the identification of the various states that an entity (in this case a person) may be in, their transitions or flows from one state to another, and the factors that determine when transitions occur. A systematic review of publications on DES in health care, in Zhang (2018), concluded that DES has "rich potential ... to provide a broader picture of ... health care systems behavior" (p.9).

Currie et al. (2020), in discussing the application of simulation modelling technique to the COVID-19 pandemic, describe DES models as being "typically used to model the operation of systems over time, where entities (people, parts, tasks, messages) flow through a number of queues and activities. They are generally suitable for determining the impact of resource availability (doctors; nurses), on waiting times and the number of entities waiting in the queues or going through the system" (p.85). The Currie article identifies a range of potential applications of DES in the context of the pandemic. In Wood et al. (2020), a report is provided of a DES model "designed to capture the key dynamics of the intensive care admissions process for COVID-19 patients" (p.1). Beyond health facility management, Bolla & Sarl (2020) model flows of COVID patients in Switzerland from home to hospital to ICU and beyond and Jalayer et al. (2020) model "citizens living, working, pursuing their needs and travelling inside a geographical environment" (p.3).

Rhodes et al. (2020) perceive models for policy to "blend various heterogeneous data (quantitative, qualitative, abstract, empirical) from various diverse contexts (different viruses, countries, localities, studies, historical periods) ... to enable a decision" (p.2). The authors discuss an "approach to the modelling of pandemics which envisages the model as an intervention of deliberation in situations of evolving uncertainty" (p.1). "The model, precisely because it has latitude as a space of triangulation and speculation, potentiates a working relationship, in which dialogue is made possible" (p.6).

Many researchers assume that DES models have to be fed quantitative data, and that the calculations are what matters. For example, the text elided from the p.2 quotation from Rhodes et al. (2020) in the previous paragraph is '[blend] into a single calculative process". This ignores the considerable limits on the usefulness of quantitative analysis in such circumstances, whether conducted mathematically or numerically by experimentation. For example, a comparison across four models of the path of COVID-19 infections in South Africa (Chi et al. 2020) found very wide variation in the models' predictions of case-counts and death-counts, highlighting the folly of reliance on any of them.

The Rhodes et al. article overlooks the fact that the 'blending', the 'deliberation', the 'speculation', the 'working relationship' and the 'dialogue' are all highly valuable in their own right, and may offer far better value to policy-makers than unverified rules applied to mediocre-quality data in a 'calculative process'. Table 1 identifies ways in which a suitable DES model can be applied in the style of a decision support system to enable Vroom-Yetton-Jago consultative or collaborative policy decision-making.

To the extent that the model is adequately articulated, tested for logical completeness, and checked against real-world activities, it is also capable of being used to simulate flows of people through the system, and 'stocks' of people currently in each state. This approach would need to be supplemented by a segmentation analysis, distinguishing in particular:

- high-risk-of-mortality categories, e.g. based on vulnerability (age, prior disposing conditions) and on intensity of exposure (health care staff);
- high-risk-of-being-highly-infective categories ('super-spreaders');
- high-risk-of-highly-infective-circumstances ('super-spreader events').

Table 1: Benefits of DES Modelling for Policy Decision Support

• The activity of building and reviewing a DES model can assist participants in gaining an **understanding** of the main states, and the main factors determining transitions between states, that are relevant to decisions about interventions and policy-settings
• That activity, through the conduct of workshops involving the relevant stakeholders, can assist in identifying differences among the stakeholders' mental models, and in achieving **commonality of understanding** of: o relevant states, and transitions among them o relevant attributes of each state and each transition; and o key terms, arising from words being used within a structured context rather than loosely in unstructured conversations
• Consideration of particular actions in light of the model enables **sharing of information and insights** into the dynamics of the real-world system(s) that policy-makers seek to influence
• When alternative strategies are being considered, the model may assist stakeholders in the **identification of key data** needed to support evaluation of

	the strategies, and hence where resources can be usefully invested in data gathering and data quality assurance, and in finding proxies for data that is too difficult or too expensive to collect
•	The model can assist in **experimentation** with the impacts that different data-values might have on the evaluation process and inferences drawn from it
•	The model can be used as a basis for pre-implentation review of conclusions reached, and pre-publication review of public statements and data, to check that important factors have not been overlooked

By manipulating key parameters (such as detection-rate; the proportion of infectees needing admission to hospital and to ICU; hospital- and ICU-capacity; treatment-periods; and mortality-rates), estimates can be made of the limits to the ability of health facilities to cope, and the extent to which urgent investment in additional facilities might be necessary.

4.3 The Postulated Model

The purpose of this research was to investigate the extent to which a DES model could support public health management in the context of an rapidly-developing epidemic. During March-April 2020, I postulated a state-transition model, intended to represent the population of a jurisdiction, and the flow of individual members of it through various states associated with infection, hospitalisation, to recovery or death. The intention was to commence with the minimum complexity, in terms of the number of states, flows, and data about each, based on the available information about the challenges that public policy-makers were addressing. The model could then be experimented with, and expanded to the extent necessary to embody a sufficiently rich understanding of the public policy problem-space. Based on government publications and media reports, and taking account of previous SEIR models, it appeared that the model would need to incorporate about a dozen states, 30-40 flows, and data-items representing the key attributes of the people passing through the system.

Although a DES model can be applied computationally, that was not the intention, because the complexities and dynamism of the relevant part of the real world are such that the results would inevitably be spurious. The model is a framing tool for the problem-space, intended to help policy-makers formalise their own mental models, appreciate and resolve differences among those models, experiment with the model, and draw inferences relevant to the many decisions they needed to make during the weeks and months of the epidemic.

The first iteration of the model, of April 2020, is in Figure 1. A textual description of aspects of the model was also developed. Broadly, individuals were conceived as beginning as Uninfected, with a proportion passing through Infection, possibly via Hospitalisation, and on to Immunity or Death. Each of the four broad domains was conceived as encompassing a number of states, such as being in hospital, or in ICU, or in a queue to get into one of them. Various aspects of each state required some articulation, and so did the conditions under which transitions occur between states.

The following section outlines the steps undertaken in order to assess the potential of this model to support public health policy decision-makers.

5 Model Testing and Articulation

During the process of postulating the model, a variety of design issues arose. Some were formal questions, such as whether and on what basis some of the state-transitions could logically arise, and could be appropriately represented.

For example, it quickly became apparent that the representation of Testing as a state was inappropriate. A more useful approach was to specify attributes of each individual, which travelled with them as they passed through the network. The key attributes appeared to be tested-awaiting-result, tested-negative, and tested-positive. That removed one state and four flows, with no loss of model richness. For ease of reading, the state Quarantined was re-numbered as (2).

Many other issues, however, were concerned with the appropriate representation of real-world states and processes. In April 2020, it was too early to resolve those issues, with the result that the model depicted in Figure 1 was provisional, even tentative.

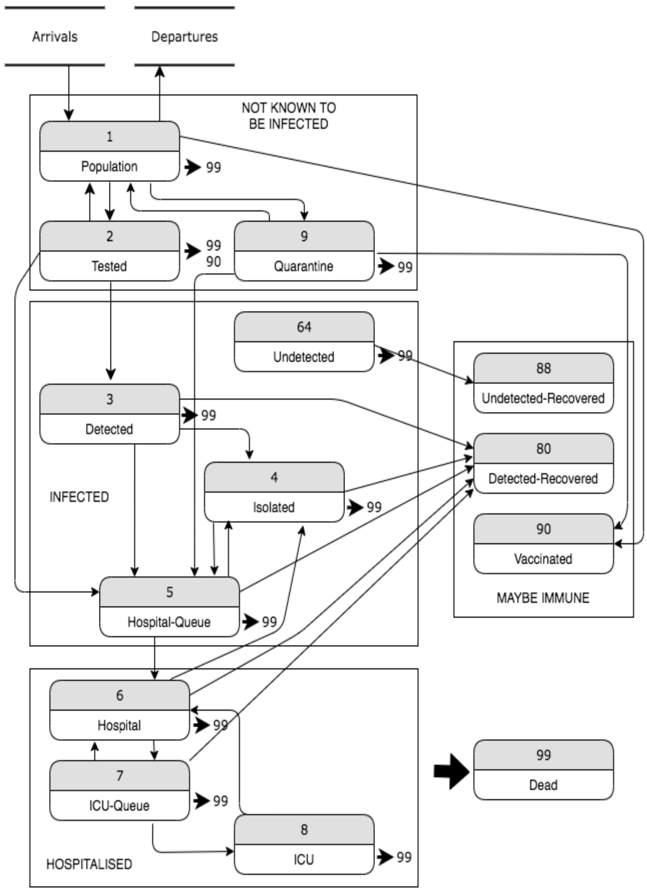

Figure 1: The Model Postulated in April 2020

In order to implement the demonstration phase of Peffers' design science method, experience needed to be gained concerning the relevant real-world systems and the appropriateness or otherwise of the representation of them in the model. A conventional way to gain such experience is through case studies. However, as the COVID-19 pandemic was only just developing, no directly-relevant case studies were available. Although case studies of other pandemics could have been sought out, it was already clear that there were distinct differences between the COVID-19 pandemic and other well-documented events, even other coronavirus events.

A more appropriate method might therefore have been to conduct a contemporaneous field study, seeking embedment within some particular jurisdiction's public health policy apparatus, and preparing a longitudinal case study of that jurisdiction's path, including uncontrolled events, interventions, and subsequent experiences. However, such access would have been very difficult to negotiate (not least in a context in which physical distancing was being imposed). It would also have to a considerable extent limited the testing and articulation process to the factors that arose in a specific jurisdiction. Each country has its own cultural context, and the events, the details of the interventions, the sequences of events, and the timings of events, varied greatly among different jurisdictions. It would be very challenging to try to draw generically useful inferences from such a field study.

An alternative approach was accordingly formulated. Monitoring was undertaken of the ongoing reporting of developments, interventions and experiences in countries worldwide. These reports provided a wide range of circumstances against which the efficacy of the model could be reviewed. This section summarises information about interventions, and identifies and briefly discusses some key themes that emerged.

Governments around the world responded to COVID-19 with a wide range of interventions intended to protect public health. A scan was undertaken of documents published by relevant international and national government agencies, including WHO (2020d) and ICAO (2020), supplemented by academic articles and media reports. Table 2 identifies mainstream public health interventions, clustered into six groups. It is important that IS and IT be brought to bear to assist policy-makers to judge the likely effectiveness of these actions in particular contexts, to design interventions, and to time and manage their implementation, adaptation and eventual withdrawal.

Because the infection-vector appeared to be primarily brief, airborne transmission from infectees to those close by, physical separation among people generally (often referred to using the misleading term 'social distancing') was widely adopted. Physical separation is also the objective of quarantine and isolation. Despite the differences in meaning, and the clear explanations provided by a range of national health agencies (e.g. CDC 2020), some agencies were not consistent in their uses of the terms. As a result, media reports evidenced considerable confusion, and it is very likely that many people were unclear about the obligations of suspects, contacts and infectees.

Table 2: The Primary Public Health Interventions

Case Discovery, Management • Identification of suspects • Quarantine of suspects • Testing of suspects • Isolation of infectees • Contact-tracing of infectees • Location of and communication with contacts	**Facility Restrictions, Closedown** • Hospitals • Aged care facilities • Institutions, e.g. prisons • Group accommodation, e.g. backpacker dormitories • Face-to-face businesses (shops, personal services, gyms) • Workplaces • Entertainment venues • Public gatherings • Geographical areas (*cordon sanitaire*) • Pre-schools, schools, tertiary educational institutions
Personal Protective Measures • Hand hygiene • Respiratory etiquette (sneeze/cough protection) • Avoidance of surfaces • Face-masks • Clinical Personal Protective Equipment (PPE) in hospitals and aged-care facilities	**Environmental Measures** • Cleaning of surfaces

Physical Distancing Measures
• Physical distancing in public places (1.5m / 4sqm)
• Quarantining of suspects
• Isolation of infectees
• 'Work-at-Home' Recommendations to Employers
• 'Stay-At-Home' Recommendations for at-risk segments
	Travel-Related Measures
	• Border restrictions
	• Border screening and testing
	• Border closure
	• Stay-at-home, work-at-home
	• Domestic movement restrictions
	    • Public transport
	    • Private vehicles
	    • Walking

Countries around the world adopted vastly different approaches to interventions, recognised different triggering events, and timed their interventions differently. Most also changed their approaches over time. Despite the enormous differences in context, some comparisons are feasible, such as among Scandinavian countries. Sweden implemented only limited actions (physical distancing, bans on large gatherings, and travel restrictions), whereas its neighbours used additional and stronger interventions to reduce the opportunity for the virus to spread, including closedown of many more categories of venue, curfews and border closures. The outcome was a death-rate per capita in Sweden during 2020 that was 4-9 times those of its neighbours (Barrett 2020).

There may also be lessons to be learnt from the juxtaposition of the apparently worst examples of mismanagement and/or outcomes (in particular, the UK, the USA, Belgium, Brazil) and the most successful (e.g. China, Singapore, New Zealand, Australia). The UK flirted with a no-action 'strategy' rationalised as striving for herd immunity, overrode professional advice, lacked coherent and consistent leadership, reacted slowly to new information, and continually changed tack in a haphazard manner (Minghella 2020). A wide range of media reports and some semi-formal reviews gave rise to the list of public health management behaviours associated with serious failure in Table 3.

On the other hand, the most successful countries acted quickly and decisively. A range of interventions, and characteristics of interventions, were associated with success in preventing spread and/or reining in spread that had already begun (e.g. OxCGRT 2020).

Table 3: Behaviours Associated with Serious Failure

- Data suppression (e.g. during the first few weeks in Wuhan)
- Disparagement of the epidemic's seriousness by national leaders (e.g. USA, Brazil)
- Disregard for public health policy advice (e.g. USA)
- Denial of the efficacy of key interventions and/or support for 'quackery' (e.g. USA)
- Delay in the implementation of constraints (e.g. Belgium, UK, Sweden)
- Inaction justified as a means to rapidly attain 'herd immunity' (e.g. UK, Sweden)

• Weak enforcement of constraints (e.g. many countries, particularly in the early stages) • Premature easing of effective constraints (e.g. many countries, particularly after the first wave)

The list of actions in Table 4 was prepared on the basis of reports about actions and outcomes in China (BBC 2020), New Zealand (Baker et al. 2020, Jefferies et al. 2020), Melbourne (Gn 2020a), and Vietnam and Taiwan (Whitworth 2020).

Table 4: Actions Associated with Success

Known-Infectee Control Measures
• Detect **infectees** early • Isolate **infectees** immediately, and perhaps household members, especially partners • Trace **close contacts of infectees** quickly • Quarantine **close contacts of infectees** • Impose closedown in and near **infection hot-spots**
Community-Spread Control Measures
• Suspend or dilute **large-scale events** in which people are closely-packed, including live entertainment, bars, clubs, churches, rallies, public transport services • Suspend **sustained-contact circumstances**, including face-to-face retail, personal services and workplaces in which physical distancing cannot be achieved
High-Risk-Segment Protection Measures
• Shield **high-risk groups**, in particular through lockdown of health and aged care facilities against non-essential entry, application in those facilities of rigid hygiene, and provision to frontline health care staff of fresh, clinical-grade personal protection equipment (PPE) • Quarantine **new arrivals into the jurisdiction**, at least until a test for infection returns a negative result

Policy-makers needed to make judgements about which interventions were needed, the specifics of their design and application, and the timing of introduction, easing, and suspension. Their judgments were affected by a great many factors. The efficacy of some actions was apparent from the beginning of the pandemic, whereas the value of other actions emerged slowly, with the gradual accretion of understanding.

In order to balance health safety against social and economic disruption, it was vital to be able to judge **the appropriate length of time for quarantine of suspects and isolation of infectees**. That depended on the ability to make reasonable determinations about the required period of confinement (requiring an estimate of when infection occurred) and the circumstances under which shorter and longer periods may be appropriate.

A guideline for discontinuing transmission-based precautions that was available in mid-2020 was that patients could be released 10 days after symptom onset plus 3-4 days without symptoms, or, in asymptomatic cases, 10 days after a positive test (WHO 2020a). In some countries, that was later variously extended to 14 days, or adjusted to permit discharge as soon as a negative test result was received. This reflected judgements made about the balance between the risk of transmission and the risk of reduced public support and hence compliance levels.

An important aspect of the public health problem is advance warning about the capacity of health facilities to cope with demand. It would be a valuable contribution if the model were able to assist in projecting **demand for and supply of hospital-beds and ICU beds**, in total, and by geographical area and hospital. This is likely to be dependent on recent testing rates, positive-result rates, hospitalisation-rates of positive cases, the proportion admitted to ICU, and the periods patients spend in those facilities. The source-data would need to be collected on an ongoing basis, in order to ensure that current indicators were readily to hand. This draws to attention another important attribute of individuals: **non-COVID admissions** to hospital queues and onwards. Factoring that in enables total demand for hospital and ICU beds to be modelled, and avoids confusing non-COVID-related transitions with those arising from the epidemic.

One of the challenging questions was the extent to which all infectees have much the same **degree of infectiveness**, or whether there are 'super-spreaders' who are much more prone to infecting other people and/or contaminating surfaces. If there is considerable variability, effort could be valuably invested in determining what infectee-attributes are associated with 'super-spreaders' and whether it is possible to focus available tracing and quarantine resources on people with those attributes. A complication arose to the estimation of infectiveness when, at the end of 2020, strains of the virus emerged that appeared to be substantially more infective.
The importance of the category of people in the the state **Undetected-Infected (64)** became apparent as the epidemic unfolded in each country, because undetected infectees are a primary source of virus-spread. In order to gain an insight into the overall progress of the epidemic at a population level, an estimate is needed of the Undetected-Infected status, for example by means of adequate random-sample testing of the public for the virus. Strategies are needed to find more of the people who are in that state, so that they can be requested or required to shift state to Isolated (4). Possibilities include extensions to contact-tracing, suspect-definition based on locations and time-periods, infection-testing in the vicinity of hotspots, and random infection-testing. It may be possible to estimate the scale of the count in Undetected (64), by random-testing for antibodies in order to develop estimates of the cumulative count in Undetected-Recovered (88), and to then reason back from there to the scale of current Undetected-Infecteds.

To reflect the uncertainties, there are benefits in using ghostly outlines to represent both Undetected-Infected (64) and Undetected-Recovered (88), and inflows to those two states. On the other hand, transitions are visible when an individual moves from Undetected (64) to Detected (3) or Hospital-Queue (5).

Considerable discussion arose about **the 'excess mortality' statistic**, and the ways in which COVID-19 affected that measure. It became clear that the terminal state Dead (99) needed to be categorised more finely. Cause of death needed to distinguish cases where COVID-19 was the cause of death, or was a significant factor in the death because it compounded prior conditions (99A) from all other causes of death, including not only where COVID-19 was not present, but also where infection was, or was assumed to be, present at death but was not listed as a cause (99B).

This phase of the research stimulated reconsideration of many aspects of the April 2020 model in Figure 1, in order to ensure that it could assist policy-makers in navigating their juridiction's particular maze. The result was the revised model in Figure 2, incorporating many adaptations reflecting the insights arising from 8 months of vicarious learning from many different jurisdictions. Further detail on the revised model is provided in the underlying Working Paper (Clarke 2021).

6 Conclusions

Despite the great contemporary enthusiasm for IT, it delivered relatively little value during the COVID-19 pandemic of 2020. This appears to have been attributable to an 'applied' approach, 'throwing technology at the problem' and at worst matching the caricature of 'when you have a hammer in your hand, everything looks like a nail'.

It appears more likely that IT can deliver for society and the economy if the approach adopted is both more strategic in nature, and 'instrumentalist' / problem-oriented rather than 'applied' / tool-oriented. That means standing far enough back to be able to identify and describe the problem-space, and then modelling the key aspects of that space. On that base, architectures, process models and data models can emerge and be refined, that will much better serve the needs of decision-makers.

The scale of activities, even within a single jurisdiction, has been so great that a detailed assessment of the models used during 2020 is difficult to assemble. The research reported in this paper comprised a mixture of thought-experiment, abstract design, and testing and adaptation of the initial model against information arising from experience across the world during the period May to December 2020.

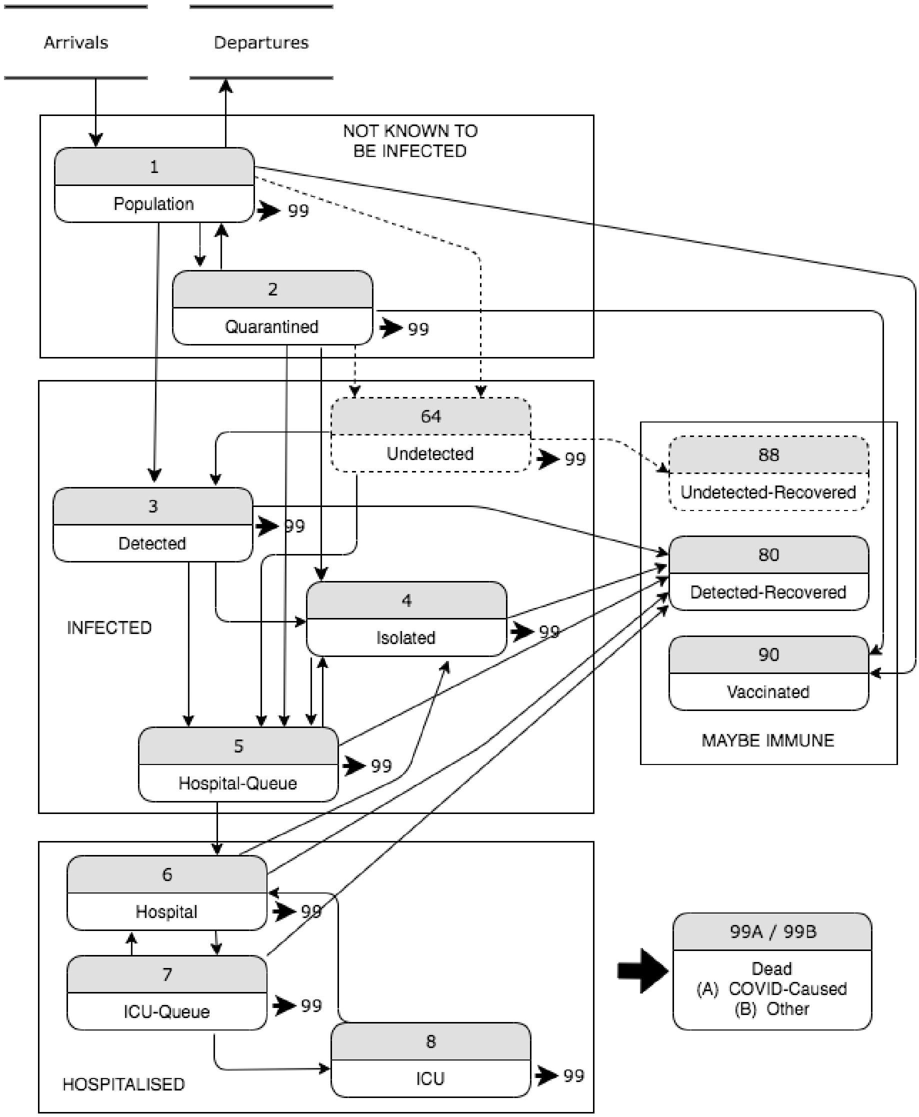

Figure 2: The Revised Model

A model was initially postulated that was envisaged as being suitable as a supporting tool for public policy decisions in relation to public health management. On the basis of new information streaming in during the subsequent months, the need for refinements was apparent. The revised model is capable of further articulation, through specification of data models in support of states and flows, and alternative processing rules for state transitions.

An example of the kind of development that requires rapid adaptation was the mid-January 2021 revelation that the hospital readmission rate for people who had recovered from COVID-19, in the UK, during January to September 2020, was 30% – 3.5 times that for the population generally – and 12% died following discharge – 7 to 8 times that for matched control groups Ayoubkhani et al. 2021). This suggests that the incidence of 'Long COVID' or 'post-COVID syndrome (PCS)' may be much higher than previously thought. It also raises questions about the extent to which people in the Recovered (80, 88) and even Vaccinated (90) states are immune to COVID-19, and even whether they are incapable of becoming infective again.

The work reported here opens up a variety of possibilities for further research, including:

- case studies of individual jurisdictions' decision processes;
- articulation of the model in specific jurisdictions;
- presentation of the model to, and workshopping with, policy-makers, in order to gain further understanding of its usefulness;
- animation of the model, in order to assist in its communication and use;
- expression of the model in a DES language such as GPSS;
- experimentation with a mix of actual data and synthetic data.

The model proposed and tested in this paper has, by its nature, limited focus. Its target-area is expressly public health management, although it has application also to the adjacent level of health facility management, and implications for population management. It is not suggested that this model subsumes or replaces models at other levels of abstraction. It is contended, however, that public health policy-makers, and government ministers and their advisers, can greatly benefit from the development, articulation and ongoing adaptation of a model of this nature. It enables processes to be better understood, strategies considered, and implications of possible interventions thought through. This information can then be combined with that arising from work at other levels of abstraction (bio-medical and medical, on the one hand, and public behaviour management and economic management on the other).

A very large number of articles have been published during 2020 in the medical, public health management and social policy literatures. In the IS discipline on the other hand, significant contributions have been few and far between. However, see Thomas et al. (2020) and Trang et al. (2020). It is contended that, unless the IS discipline adopts considered, strategic approaches to public policy needs, proponents of IT will be dismissed as 'technological solutionists' and even 'delusionists', and IT and IS will lose their lustre.

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