Co-Designing Capabilities for a Robust Pandemic Response

Stakeholder Engagement for Visioning, Backcasting, and Evaluating New Decision-Support Capabilities
This paper reports on a stakeholder engagement process to inform research aimed at improving public health officials’ response to future pandemics. The authors convened three workshops as part of the Robust Epidemic Surveillance and Modeling (RESUME) project - an NSF-funded Predictive Intelligence for Pandemic Prevention (PIPP) Phase I effort. The workshops convened public health decision-makers, modelers, and researchers to envision a future with improved pandemic response, demonstrate means for co-producing research plans to pursue that vision, and inform the design of specific information products using Robust Decision Making methods that could support robust public health decisions in such a future. At the start of this project, we conducted a backcasting exercise with our public health partners, asking them to imagine that it is 2035 and that their agency has successfully managed a pandemic. We also asked them to describe the information and decision-support tools that helped them achieve this happy result. The project team extracted from these stories a list of research priorities. We then conducted a decision-framing workshop focusing on a subset of these priorities, a specific pandemic response decision, and the information our partners would want to address the challenge. The project team then conducted a pilot analysis based on this decision framing and presented proof-of-concept visualizations of the results. We then gathered stakeholders’ opinions about the perceived utility of the analysis and discussed future research agendas.

Social and Behavioral Policy Program

RAND Social and Economic Well-Being is a division of the RAND Corporation that seeks to actively improve the health and social and economic well-being of populations and communities worldwide. This research was conducted in the Social and Behavioral Policy Program within RAND Social and Economic Well-Being. The program focuses on such topics as risk factors and prevention programs, social safety net programs and other social supports, poverty, aging, disability, child and youth health and well-being, and quality of life, as well as other policy concerns that are influenced by social and behavioral actions and systems that affect well-being. For more information, email sbp@rand.org.

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Chapter 1. Introduction

The COVID-19 pandemic highlighted the need for advanced analytics in public health institutions to support agile, robust, and inclusive pandemic response policies. Although modeling played a crucial role in informing decisions, its use was fragmented, and key modeling ad hoc capabilities had to be created to support decisions. Despite widespread efforts to inform policies with models, critical decisions lacked appropriate and timely analytic support. Effective, transparent, and equitable pandemic response policymaking will benefit from information products based on the best available science tailored to meet the demands and challenges faced by public health decision-makers. Best available science includes information products whose design is informed by the best available understanding of the science of decision support.

The Robust Epidemic Surveillance and Modeling (RESUME) project is an NSF-funded Predictive Intelligence for Pandemic Prevention (PIPP) Phase I center development grant with investigators from Argonne National Laboratory, the University of Chicago, RAND Corporation, Northwestern University, Virginia Tech, and INRIA. The project seeks to improve on critical gaps for effective PIPP capabilities.

As part of this project, we carried out a stakeholder engagement process consisting of three workshops, as shown in Figure 1.1. Workshop participants included public health decision-makers and modelers from public health departments (Chicago, California, Illinois, and Cook County) and the CDC. This engagement process was designed both to inform the design of specific Multi-Objective Robust Decision Making (MoRDM)-based information products useful for public health officials as well as to demonstrate methods for co-producing the research plans for the RESUME Phase I activities and the Phase II center proposal.

Figure 1.1. Stakeholder Engagement Process Overview
This document describes the three stakeholder engagement workshops conducted from November 2022 to October 2023, which informed the direction of six pilot studies conducted as part of the RESUME Phase I center grant and provided direction for a Phase II center proposal. The first workshop sought to generate an initial shared vision for how next-generation data, modeling, and decision support capabilities could significantly improve current pandemic prevention, predictive intelligence, and response. The workshop included a backcasting exercise, asking stakeholders to imagine a vastly improved response to a pandemic ten years hence and to describe the new science-enabled capabilities that made the response possible. In the second workshop, policymakers identified key policy levers, uncertainties, and outcome measures they need to consider when making public health decisions during a pandemic. In the third workshop, participants provided feedback on a proof-of-concept analysis that aimed to demonstrate how critical decisions could be informed by advanced analytics that could aid decision-makers in balancing conflicting societal goals while accounting for and hedging against uncertainty. This paper summarizes each workshop including feedback received from public health stakeholders.
Chapter 2. Visioning Workshop

On November 14, 2022, the RESUME team hosted the first of the three stakeholder workshops in person at the University of Chicago. In addition to hosting the RESUME research team from institutions across the country, this full-day visioning workshop convened public health decision-makers and modelers from the CDC, the California Department of Public Health, the Illinois Department of Public Health, the Cook County Department of Public Health, and the Chicago Department of Public Health.

The workshop aimed to generate an initial shared vision for how next-generation data, modeling, and decision support capabilities might significantly improve current pandemic prevention, predictive intelligence, and response. Appendix A contains the agenda for the full-day workshop. We began the workshop with a backcasting exercise, asking stakeholders to imagine a vastly improved response to a pandemic 10 years hence and to describe the new science-enabled capabilities that made the response possible. We next asked public health departments to describe the current data sources they use for decision-making and the decision-making processes created during the COVID-19 pandemic. Then, members of the RESUME team gave lightning talks describing their planned research under our Phase I pilot grant. Finally, we conducted a group exercise to identify gaps between the future vision and current capabilities, identifying which gaps can be addressed by the RESUME team through the planned pilot studies and a potential NSF Phase II PIPP grant or future projects.

Backcasting a Vastly Improved Pandemic Response

After introducing the project's scope and the purpose of the day, public health stakeholders and the full RESUME research team were presented with a backcasting exercise. A backcasting exercise seeks to generate a vision by describing the world's desired future state and identifying near-term steps that enable such a vision to materialize. In this exercise, stakeholders were asked to imagine a future where the pandemic response was vastly improved, and their public health department was applauded for an exemplary response.

Box 2.1 shows the scenario presented to workshop participants. After being presented with this scenario, participants were assigned to four breakout groups. Each breakout group had a set of participant roles: a rapporteur, a facilitator in charge of distilling the key points into a PowerPoint slide, and a note taker from our research team, and group members. The rapporteur

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was a public health decision-maker elected by the group, whereas the facilitator and note-taker were selected by the research group. Notes were taken such as not to preserve any personal identification. After the breakout session, each rapporteur presented a narrative to all their groups describing the main events that led to their group’s successful pandemic response. They then described key new analytic capabilities that enabled them to achieve those outcomes.

<table>
<thead>
<tr>
<th>Box 2.1. Backcasting exercise: A pandemic strikes in 2035</th>
</tr>
</thead>
</table>

*A Pandemic Strikes in 2035, and your Jurisdiction has the Nation’s best response. How did you do it?*

- You run the health department of a state or large city.
- A deadly, highly contagious pathogen recently appeared in the U.S.
- Your jurisdiction’s response was exemplary.
- You’ve been invited onto a podcast with an audience of millions to tell your story of what went right.
- What will you say?

**Envision this timeline:**

2. What capabilities were put in place to Enable your success?  
   1. Describe your successful pandemic response

2022 --------------------------------------------------------------2035

*Create a narrative describing how your jurisdiction achieved this success.*

In telling the story, address:

- What key capabilities did you have in 2035 that your predecessors lacked in 2020?
  - Capabilities available to your jurisdictions
  - Capabilities at the federal level
- How did you make use of these capabilities?

**SOURCE:** Adapted from workshop briefing slides. The authors.

Figure 2.1 presents the authors’ consolidated list of the capabilities identified by the workshop participants, ordering along a spectrum ranging from *analytic* to *community engagement* capabilities. The former end of this spectrum contains analytic capabilities that can inform decisions based on the best available science, whereas the latter includes capabilities needed to mobilize communities, build and sustain trust in public health officials, and effect change in the real world.
Figure 2.1. Capabilities for Improved Pandemic Response

- Characterization of potential pathogens
- Pathogen early detection
- Estimation of disease transmission and incidence distribution
- Data integration
  - Data collection
  - Pre-existing data agreements
  - Data set integration
- Pre-emptive scenario modeling
- Optimization of NPI decision thresholds
- Rapid development of diagnostics and treatments
- Model validation
- Ability to reuse the models across contexts.

- Behavior surveillance to inform modeling and response (i.e., mixing, vaccination, "trust").
- Matching mitigation options portfolio (and their interactions) to different pathogens
- Understanding of impacts on different groups and societal sectors
- Portfolio analysis/optimization with learning over time (including how to remove restrictions)
- Infrastructure for ongoing collaboration between agencies, researchers and public
- Understanding and building public health resilience into existing operations
- Connect response drills / modeling to a wide range of disease severity
- Scenario exercises/pandemic response drills (i.e., using cellphone data)
- Surveys and focus groups for messaging
- Data protection and security protocols for data sharing
- Participatory exercise to promote response coordination among different organizations and jurisdictions
- Situation awareness process for keeping decision makers up to date on the research pipeline
- Criteria for establishing trust among populations leveraging behavioral science
- Uncertainty communication
- Better understanding of the flow of information and trust in populations (i.e., with network analysis)

SOURCE: The authors, based on information elicited during the backcasting exercise.
Identifying Research to Close Capability Gaps

After discussing the list of capabilities listed in Figure 2.1, participants were again assigned to breakout groups and were tasked with choosing three or four capability areas close to the analytic end of the spectrum2 and were asked to describe: i) what gaps exist between the envisioned future and current capabilities, and ii) what research a future RESUME grant could conduct to close those gaps. Each group had thirty minutes to discuss and then reported back to the broad group the areas that they prioritized. Here, we describe a synthesis of those key capability areas prioritized by participants.

Data and Model Integration

The lack of a centralized resource to access and process data is a significant challenge for public health stakeholders and researchers. Access to certain data types, such as those held by hospitals or public agencies, can be difficult. There are significant privacy concerns associated with data sources used in epidemiological modeling, such as hospitalizations and case counts. A proposed solution was expanding the creation and use of statistically representative synthetic datasets to address privacy concerns and incomplete or missing data. In addition, many administrative data sources are inconsistent across agencies and difficult to ingest. Developing infrastructure and standards around data reporting enables better collaboration across municipalities and is essential to support public health decision-making. In addition to access and ingestion, there was a call for better infrastructure to support multi-modal data and model integration. There is a need to merge various levels of modeling—from macro-level societal factors like housing and employment to detailed biological data. This integration requires the development of interoperable systems that can handle diverse data types, including sensor, epidemiological, and social-behavioral data.

Behavioral Surveillance

Behavioral patterns are crucial to understanding the epidemiological trajectory, as behaviors can change rapidly in response to new information. Understanding the feedback loop between the implementation of interventions and subsequent changes in behavior is key for public health stakeholder to assess their decisions. However, monitoring these behaviors is difficult and raises privacy concerns. Tools like behavioral surveys can offer insight into how people may react to an infectious disease outbreak or a public health intervention, but these can be biased and not necessarily reach the most vulnerable populations. More direct surveillance like economic,

2 This exercise focused on analytic capabilities because that was the focus of our proposed NSF PIPP Center. Still, one could also develop research or community engagement activities that would help close gaps in the other end of the spectrum.
traffic, or cell phone data may paint a more accurate picture of people’s movement and activities, but questions remain regarding how to enroll folks in these types of surveillance programs who are already resistant to public health messaging.

**Messaging and Uncertainty Communication**

A key concern in public health messaging is retaining public trust while communicating uncertain or divergent model results. To get public buy-in, officials must communicate the expected uncertainties across disciplines and methods and be clear about how and why certain decisions are being made, even considering these uncertainties. It is important to avoid confusion and not be presumptive of what types of impacts will be most valuable to the decision-making entities. In addition, the public should understand what types of data are being collected and why, and a legal framework should be established for using datasets that the public perceives as privacy-violating. This requires an ongoing education process, in addition to research into how to make using data more palatable.

**Research and Policy Integration**

Building trust and fostering collaborative relationships between research entities and public health departments is essential for a more streamlined future pandemic response. Task ownership should be established early in the relationship, and the research focus should be on implementation rather than a typically exploratory research framework, given the time and resource constraints surrounding public health emergencies. Researchers could make more of an effort to communicate their modeling efforts qualitatively and should present a more unified framework in the face of uncertainties. Relationship building between public health departments and researchers is paramount and should be ongoing, even in non-pandemic times.
Chapter 3. Decision Framing Workshop

On February 17, 2023, we held the second workshop, an online decision-framing activity with public health stakeholders. Participants included decision-makers and modelers from public health departments that partnered with the RESUME project, including the California, Illinois, and Chicago departments of public health and the CDC. The workshop aimed to characterize decision-making challenges public health officials face during a pandemic, seeking to identify decision problems that could be informed by new decision-analytic capabilities to be developed during a Phase II Center grant. We could not pilot-test all capabilities listed in Figure 2.1; hence, we used the second workshop to frame a decision challenge related to capabilities closest to our prior work.

Following a typical Robust Decision Making process, we used the XLRM framework to organize stakeholder input regarding common elements that shape pandemic response decisions. The XLRM decision-framing exercise identifies exogenous uncertainties (X), policy levers (L), relationships (R), and outcome measures (M) that constitute a decision-making challenge faced by decision-makers. Such an exercise allows decision-makers to articulate their priorities. Box 3.1 presents the decision-framing scenario presented to workshop participants.

After being briefed on the workshop’s purpose and presented with the decision scenario in Box 3.1, stakeholders were placed into three breakout groups and used the XLRM framework to help frame decisions they would have to make in a similar pandemic. We did not elicit information about relationships (R) because we intended to use a variation of the model used in our prior work, and discussing modeling details was beyond the scope of our workshop. The following sections provide the authors’ summary of the Outcome Measures, Policy Levers, and Uncertainties discussed during the workshop. Appendix B provides a more complete list of the decision-framing elements as discussed by participants.

Outcome Measures

Outcome measures define the goals decision-makers try to achieve during a pandemic. These measures are grouped into six categories: *health outcomes*, *health outputs*, *economic and social outcomes*, *equity outcomes*, *behavioral outcomes*, and *process measures*. *Health outcomes* include the number of cases, hospitalizations, deaths, and healthcare system utilization. *Health outcomes* include the number of cases, hospitalizations, deaths, and healthcare system utilization.

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outputs include test positivity, resource availability, and overall disease transmission. Economic and Social Outcomes encompass the economic costs of intervention and disease incidence, the mental health and educational effects of interventions, and the overall impacts of the pandemic on social interactions. Equity outcomes are crucial because all the outcomes listed before may not be evenly distributed across the population. For example, certain population groups might bear a disproportional share of the economic and health effects of the pandemic. Stakeholders also listed behavioral outcomes, including the public's trust in public health officials, the degree of buy-in for proposed interventions, and the degree of compliance with interventions. Finally, stakeholders identified a set of process measures for the pandemic response process. These measures included agility, appropriateness, stability, and transparency of pandemic response decisions.

**Box 3.1. Pandemic Response Decision Framing Exercise**

- A new airborne SARS-CoV-2-like pathogen emerged and already is under circulation in all continents.
- R₀ was estimated to be 3 at the pandemic onset, population has little to no immunity against the new pathogen.
- mRNA vaccine manufacturers have phase-3 trials well underway. It is expected that vaccines will take at least 6 months to be rolled out, but the extent to which the vaccine will provide sterilizing immunity is unclear.
- US states are adopting widely different strategies.

**What strategies should your public health department take to control this pandemic over the coming months?**

Use the XLRM framework to create a list of Uncertainty Factors (X), Policy Levers (L), and Outcome Measures (M) that influence your response to the pandemic. Your group does not need to discuss the relationships (R) (i.e., models) that can be used to inform those decisions at this stage.

<table>
<thead>
<tr>
<th>Uncertain Factors (X)</th>
<th>Policy Levers (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>What uncertain factors outside decision makers' control affect their ability to pursue their goals?</td>
<td>What actions might they take to pursue their goals?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Relationships (R)</th>
<th>Performance Metrics (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>How might policy levers (L) and uncertainties (X) be related to decision makers' goals (M)?</td>
<td>What are decision makers trying to achieve?</td>
</tr>
</tbody>
</table>

The figure below illustrates the relationships between each of the elements of the XLRM framework.

SOURCE: Workshop briefing slides. The authors.
Policy Levers

Stakeholders identified a broad set of policy levers – actions that decision-makers can take to pursue their goals – they would use in the scenario described. The policy levers identified were grouped into categories, including nonpharmaceutical interventions, resource allocation strategies, interagency coordination, data collection, communication and community engagement, and research and analysis.

Nonpharmaceutical interventions (NPIs) include social distancing, business closures, masking mandates, contact tracing, and other measures used during the COVID-19 pandemic. Stakeholders also mentioned the rules used to introduce or remove such interventions as decision levers, including disease thresholds used to introduce or remove interventions. Resource allocation strategies include various decisions to make resources available across time, space, and population groups. Those include vaccination, rollout strategy, building health testing capacity, and making treatments available across geographies. Resource allocation strategies also included optimizing care settings, primarily primary care, for the pandemic response. Interagency coordination included the promotion and investment in coordination among and within states, the establishment of a command structure integrating multiple agencies, waving of long administrative processes, swift procurement of supplies, the establishment of special emergency orders, gathering our funding to implement those programs, and other efforts.

Public health decision-makers mentioned data collection as a policy lever to inform other decisions. That category included synchronizing data sets and reporting requirements, integrating data systems, monitoring trends, and making the data available to the public. Participants also emphasized Communication and Community Engagement as a key policy lever category. Communication included the proclamation of emergency orders, including uncertainty communication about the effects of policies, treatments, and vaccines. Stakeholders also mention conducting research and analysis as a policy lever that included obtaining funding and encouraging specific types of research to achieve a balanced research portfolio that can inform relevant pandemic response decisions. They also mentioned the establishment and use of scientific advisory committees as a strategy to support other decisions.

Uncertainties

Uncertainties are factors outside decision-makers' control that affect their ability to pursue their goals. Uncertainties identified by participants were grouped into three main categories: disease characteristics, intervention effectiveness, and social and behavioral response. Disease characteristics include a range of variables that affect health outcomes and the nature of disease throughout an infection. These variables include transmissibility, severity, the clinical spectrum of an infection, pathogen mutation, immunity dynamics, modes of transmission and heterogeneity of susceptibility to the disease and heterogeneity of transmission across settings. The intervention effectiveness category includes variables that affect policy decisions and the
ability to effect change in the physical environment, including the capacity and velocity to gather information, the effectiveness of nonpharmaceutical intervention efforts, and the effectiveness of treatments and vaccination. Social and behavioral response uncertainties include uncertainties about the socio-political environment where decisions are made and include political willingness to respond to a new pandemic, public support and adherence to interventions, the effect of (mis)information on adherence to interventions, and scientists’ and influencers’ beliefs about disease characteristics and relative costs and benefits of interventions. Despite calls for the consideration of adaptive behaviors in infectious disease models, this is still a nascent area in infectious disease modeling.

Chapter 4. Demonstration and Feedback Workshop

We convened our third workshop remotely on October 6, 2023. One topic raised by participants in the second workshop involved the rules public health officials might use to introduce and remove NPIs during a pandemic. We focused the third workshop on presenting decision tools relevant to this question because we could do so building on our previous work.3

The third workshop started with a presentation of proof-of-concept decision products from a pilot Many-Objective analysis6 of rules for introducing and removing NPIs to public health stakeholders. Then, we presented public health decision makers with hypothetical questions, which they answered using interactive decision-support aids provided. Finally, stakeholders provided feedback about the content of the analysis presented, as well as on how analyses like these could be improved to better inform pandemic response. To our knowledge, this was the first instance in which public health decision-makers participated in a Decision Making under Deep Uncertainty (DMDU)7 participatory process where they participate in problem framing (through our second workshop), were briefed on the results of the analysis, and interacted with decision aids to deliberate over decisions.8 The following sections present the decision problem and proof of concept analysis presented during the workshop.

Decision Problem

Figure 3.1 illustrates the reasoning for introducing non-pharmaceutical interventions. The tiered intervention plan on the right panel showcases different intervention levels and colors that represent a set of actions taken by public health decision-makers to minimize infectious contacts that can lead to disease. The plan works by monitoring disease incidence and taking appropriate action when it exceeds pre-defined thresholds. This response plan involves two decisions: a disease incidence intervention threshold that triggers interventions if crossed, and the date when all interventions are removed.

Figure 3.1. Rationale for Pandemic Policy Response

(1) Choose

- Maximum intervention level
- Intervention thresholds: cases per 100,000 people that trigger new intervention level
- No intervention

Decision 1: Intervention thresholds

Decision 2: Intervention duration
time: date when all interventions are removed

(2) Given

(a) Infection fatality ratio: we learn how to treat the disease over time
(b) Fatality Risk Ratio: hospitals run out of staff and supplies when overwhelmed

Time: Healthcare utilization

SOURCE: The authors.
NOTES: The upper panel (1) illustrates two decisions that policymakers must make as they decide how to respond to a new pandemic: intervention thresholds (i.e., the disease incidence they wait to see until a new intervention is introduced) and intervention duration (the amount of time the intervention regime is in place). Other decision includes what interventions are introduced within each intervention level, represented as colors. Policymakers choose those policies given a set of beliefs and facts about the pandemic dynamics (panel 2), including (a) that the disease fatality ratio decreases as standards of care improve and (b) that hospitals and healthcare systems can be overwhelmed by a new pandemic as their resources depleted in an outbreak.

The lower panel of Figure 3.1 shows two reasons why decision-makers may adopt such a phased plan. First, medical vaccine treatments have been proven to make a new pathogen less deadly over time. During the pandemic, we observed a reduction in the infection fatality rate on the order of 40% after the first few months of the pandemic as standards of care evolved. Secondly, hospital resources are not infinite, and they can be overwhelmed by a new pandemic if too many hospitals exceed their capacity. During the COVID-19 pandemic, hospitals across the country were overwhelmed, and many countries even observed hospitals running out of oxygen as COVID-19 cases overwhelmed hospital capacity. Hence, the second rationale for a phase response plan is to curb the exponential growth of a new infectious pathogen by limiting transmission so that hospital capacity is not overwhelmed. These factors, along with other
parameters that describe disease characteristics such as hospitalization rates, characterize the decision problem of balancing the benefits of limiting disease transmission of a new pathogen with the cost of introducing those interventions.

**Analysis Generates Sets of Efficient Policies**

Figure 3.2 compares two sets of alternative rules for introducing and removing NPIs. The two policies are: *fixed duration* policies hold the duration of the pandemic response plan at 150 days (i.e., the time horizon of the simulation exercise) and vary the case thresholds that trigger interventions, while *variable duration* policies jointly optimize the duration of intervention and case thresholds as to achieve the lowest number of deaths at the lowest possible cost. We obtained the latter set of policies using an evolutionary many-objective optimization algorithm (NSGA-II)\(^9\) and a disease transmission model similar to the one used in our prior work\(^10\), and economic assumptions in line with economic modeling that estimated the effects of non-pharmaceutical interventions as seen in our prior work. These results were produced for proof-of-concept purposes and should not be treated as predictions or projections.

These pilot results illustrate that policies obtained through the many-objective optimization procedure meaningfully outperform policies with a fixed duration. For example, a policy with a fixed duration of 150 days that results in 700 deaths per 100,000 people resulted in a cost of $18,000 per person. Policymakers can improve both health and economic outcomes by choosing a better policy. For instance, the simulation shows it would be possible to reduce deaths from 700 to 400 deaths per 100,000 people, holding costs constant or reduce costs to $14,000 per person without increasing the number of deaths. The policies that produced better results were generally more stringent, initially avoiding surges that overwhelmed hospitals in the early days of the pandemic while suspending interventions later when the pandemic was closer to the end of the simulation period (when a vaccine is assumed to be introduced). Hence, these results demonstrate that societal outcomes could be improved if policymakers carefully calibrate the intervention intensity and duration using the approach explored in this pilot study.


Source: The authors.

Notes: Each point represents one policy solution to the pandemic response problem – i.e., a combination of intervention threshold and overall duration illustrated in Figure 1. Fixed duration strategies (crosses) set the intervention duration to 150 days (the timeframe of the simulation) and vary the case threshold. Variable duration (circles) strategies are those obtained by a many-objective optimization algorithm and jointly optimize intervention duration and decision threshold to minimize deaths and costs. The figure demonstrates that fixed-duration strategies are outperformed by strategies obtained through the optimization routine, resulting in both higher costs and deaths.

Uncertainty Shapes Policy Decisions and Tradeoffs

Figure 3.3 shows the impact of intervention effectiveness on policy outcomes. In the prior figure, we assumed an intervention effectiveness of 15% for each intervention level, reducing infectious contacts by 15%. In Figure 3.3, we show how policymakers' optimal policies might change with higher or lower intervention effectiveness. For instance, if policymakers only achieve a 12% intervention effectiveness, they cannot reduce deaths to the same extent at any level of cost relative to the death reduction that they would achieve with higher intervention effectiveness. On the other hand, higher intervention effectiveness helps reduce pandemic-related deaths.

11 From a cost-effectiveness analysis standpoint, the set of “circle” strategies form a cost-effectiveness frontier. Note that we do not remove extended-dominated strategies (i.e., strategies that are dominated by a linear combination of two strategies) from the frontier because in this case, policymakers cannot combine strategies by assigning a proportion.
deaths at a lower cost and could even lead to eliminating the disease locally within the simulation, if society is willing to bear the societal costs associated with that outcome.

Figure 3.3. Intervention Effectiveness Shapes Policy Decisions and tradeoffs

The effectiveness of interventions depends on multiple factors, including public trust, good communication, intervention choices, targeting the transmission modes, and adherence to mitigation behaviors. These findings show that achieving a high intervention effectiveness is crucial for the success of a pandemic response plan.

The effectiveness of interventions influences the response to the pandemic; however, other disease characteristics can also influence decision outcomes. For instance, new variant strains with higher transmissibility can emerge, which can change the tradeoff decision-makers face. Figure 3.4 presents twelve Pareto surfaces under different intervention effectiveness and
transmissibility scenarios represented by different $R_0$ values, the initial reproductive number (i.e., the average number of people one infected person infects over the course of the disease when the population is completely susceptible). The figure illustrates that pathogens with lower transmissibility can be controlled at a lower cost, whereas higher transmissibility requires a higher societal cost to mitigate deaths. Moreover, the number of deaths under the no-intervention scenario reflects that higher transmissibility is more likely to cause severe cases of hospital capacity overload. This increase in the effective infection fatality rate occurs because when hospitals are full, there is no capacity to offer appropriate care for all patients, resulting in more patients dying unnecessarily because of a relentless outbreak. Together, the twelve Pareto frontiers show that the outcomes policymakers can achieve depend critically on biological and socio-economic uncertainties.

**Figure 3.4. Pareto Frontiers Quantify the Effect of Uncertainties on Policy Trade-offs**

![Figure 3.4. Pareto Frontiers Quantify the Effect of Uncertainties on Policy Trade-offs](image_url)

**SOURCE:** The authors.

**NOTES:** Each point represents one policy solution to the pandemic response problem, obtained via many-objective optimization. Colors represent NPI effectiveness, and panels (different $R_0$ values) represent different initial reproductive numbers – i.e., the expected number of people that an infected individual will infect over the course of
their infection. The figure illustrates that the tradeoffs faced by policymakers hinge critically on the combined effects of interventions and biological parameters, both of which are uncertain and geographically heterogeneous at the outset of the pandemic and can change with the introduction of new variant strains.

Interactive Decision-support Tool Facilitates Tradeoff Analysis

We developed a pilot decision support tool to allow policymakers to interact with the results of our analysis (Figure 3.6) so that they could familiarize themselves with its capabilities and we could evaluate the tools’ ability to convey information to its users. After being briefed on the analysis results discussed previously, public health stakeholders were asked to use the interactive decision-support tool to make hypothetical decisions. The tool showcased a range of model-simulated outcomes as the user hovered over each policy choice, including both health outcomes (i.e., deaths caused by the pandemic, as well as probability and duration of healthcare systems overload) and economic outcomes (estimated costs of nonpharmaceutical intervention and duration of interventions). After first exploring the decision support tool, policymakers were to select a policy based on hypothetical scenarios.

After using the decision-support tool and making a small set of hypothetical decisions, policymakers were asked to discuss the usefulness of the provided information for decision-making, what information was not available in the decision-support tool but could be helpful, and whether and how the information provided would change their decisions.

Figure 3.6. Pilot Decision-support Tool Allows Exploration of Policies and Tradeoffs

![Image of the decision-support tool](image-url)
NOTES: This interactive visualization pilot tool was designed to allow workshop participants to filter policies based on scenarios. The tool showed further details about simulated outcomes as users filtered and hovered over policy options. Additional tool tabs (not shown) presented additional outcomes, such as regret (i.e., distance from simulated optimal) outcomes.

Stakeholders Suggest Direction for Future Research

After interacting with the decision support tool and making hypothetical decisions, participants discussed suggestions for improving the analysis presented. Their suggestions can be grouped into four categories: additional policies and outcomes to consider in the analyses, communication issues, and the need to investigate when nonpharmaceutical interventions should be removed.

First, participants expressed interest in exploring a wider range of policies and in modeling those policies in more detail. One participant suggested that analyses like the one presented could model specific interventions more explicitly, suggesting differential intervention thresholds and durations for them. Other participants also suggested the need to account for decision delays in addition to surveillance delays, which can hinder the effects of policy.

Participants also expressed interest in assessing outcomes that are frequently out of the scope of disease transmission models but are nevertheless critical, such as the mental health impacts of interventions. Furthermore, participants underscored the need to account for policy stability and avoid introducing and removing interventions repeatedly, as this can create confusion and undermine trust in public health decision-makers.

Participants also highlighted the challenge of using decision analytic tools for informing nonpharmaceutical decisions during a pandemic, particularly in terms of communicating the decisions to the public and avoiding conveying precise estimates. To address this, some participants suggested that decision analytic tools must be developed and designed to facilitate communication of results for a wide range of decision-makers from a wide range of political views, including those in principle opposed to government intervention. In such cases, the tools can emphasize healthcare capacity constraints and allow decision-makers to understand the decision problem from a wider range of perspectives.
Chapter 5. Conclusion

The three workshops facilitated stakeholder engagement throughout the RESUME Phase I project. We identified analytical capabilities to enhance the pandemic response, clarified the decisions to be informed by such new capabilities, pilot-tested Robust Decision Making as a capability to support pandemic response decisions, and gathered feedback from public health modelers and decision-makers with real-world experience. The findings from these exercises informed the development of our PIPP Phase II proposal and, more broadly, offer an example of how pandemic response decision-making capabilities can be enhanced by using methods developed in other fields.

Stakeholders were engaged throughout this process and expressed interest in using new decision-analytic capabilities explored in this project. They recognized similarities between the decision-making approach we demonstrated and the intuition that guided some of their decisions during the COVID-19 pandemic. For example, decision-makers recognized that the decision-analytic method of minimizing regret over multiple futures underlies their decision to introduce early interventions to reduce COVID-19 transmission, even if they did not use a formal decision-analytic approach in the early days of the COVID-19 pandemic.

Limitations

This work is not without limitations. First, the modeling results shown should be viewed as a proof-of-concept illustration. While the scenarios and examples we used mirrored the COVID-19 pandemic, the overall approach could inform public health decisions to tackle other infectious diseases. Second, we did not explore the entire range of MORDM methods, and we did not execute a demonstration of the scenario discovery step in the MORDM analysis. Third, the stakeholders that participated in our workshop were those who partnered with the RESUME project rather than a representative sample of stakeholders. Fourth, our second and third workshops were conducted remotely, and participation could be improved with in-person interaction. Finally, a formal evaluation of the pilot MORDM application was outside of the scope of this project but could reveal further insights, especially if conducted with public health stakeholders from jurisdictions representing a wider range of the political spectrum. To address these limitations, future work could focus on evaluating alternative communication strategies to assess the extent to which the information produced by these analyses is understood by decision-makers, and to understand how best to communicate those to the public.
## Appendix A. Workshop Agendas

### Table A.1. Visioning Workshop Agenda

<table>
<thead>
<tr>
<th>Time</th>
<th>Item</th>
<th>Presenter</th>
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<tbody>
<tr>
<td>09:00 - 09:10</td>
<td>Introductions</td>
<td>Jonathan Ozik</td>
</tr>
<tr>
<td>09:10 - 09:40</td>
<td>Welcome and RESUME project overview</td>
<td>Jonathan Ozik</td>
</tr>
<tr>
<td>09:40 - 09:50</td>
<td>Overview of day</td>
<td>Robert Lempert</td>
</tr>
<tr>
<td>09:50 - 10:05</td>
<td><strong>Pandemic Response Backcasting Exercise</strong></td>
<td>Robert Lempert</td>
</tr>
<tr>
<td></td>
<td>Backcasting exercise introduction</td>
<td></td>
</tr>
<tr>
<td>10:05 - 10:55</td>
<td>Break-out groups</td>
<td>-</td>
</tr>
<tr>
<td>10:55 - 11:10</td>
<td>Coffee break</td>
<td>-</td>
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<tr>
<td>11:10 - 12:00</td>
<td>Break-out groups report back</td>
<td>-</td>
</tr>
<tr>
<td>12:00 - 12:50</td>
<td>Lunch break</td>
<td>-</td>
</tr>
<tr>
<td>12:50 - 13:05</td>
<td>Pandemic Response break-out session synthesis</td>
<td>Robert Lempert</td>
</tr>
<tr>
<td>13:05 - 13:10</td>
<td>Intro to lightning talks</td>
<td>Jonathan Ozik</td>
</tr>
<tr>
<td>13:10 - 14:10</td>
<td>Pilot studies lightning talks</td>
<td><strong>Pilot Study Leads</strong></td>
</tr>
<tr>
<td>14:10 - 14:20</td>
<td><strong>Pandemic Response Capability Gaps Exercise</strong></td>
<td>Robert Lempert</td>
</tr>
<tr>
<td></td>
<td>Capability Gaps Exercise Introduction</td>
<td></td>
</tr>
<tr>
<td>14:20 - 15:00</td>
<td>Break-out groups</td>
<td>-</td>
</tr>
<tr>
<td>15:00 - 15:10</td>
<td>Coffee break</td>
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<tr>
<td>15:10 - 15:45</td>
<td>Break-out groups report back</td>
<td>-</td>
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<tr>
<td>15:45 - 15:55</td>
<td>Break-out session synthesis</td>
<td>Robert Lempert</td>
</tr>
<tr>
<td>15:55 - 16:00</td>
<td>Next steps</td>
<td>Jonathan Ozik</td>
</tr>
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</table>

SOURCE: The authors.
### Table A.2. Decision Framing Workshop Agenda

<table>
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<th>Time</th>
<th>Item</th>
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<tbody>
<tr>
<td>12:00 - 12:05</td>
<td>Introductions</td>
<td>Jonathan Ozik</td>
</tr>
<tr>
<td>12:05 - 12:15</td>
<td>Introduction to MORDM and the XLRM framework</td>
<td>Robert Lempert</td>
</tr>
<tr>
<td>12:15 - 12:20</td>
<td>Decision framing exercise setup</td>
<td>Robert Lempert</td>
</tr>
<tr>
<td>12:20 - 12:50</td>
<td>Break-out groups discuss decision framing</td>
<td>Robert Lempert</td>
</tr>
<tr>
<td>12:50 - 13:20</td>
<td>Breakout groups report back</td>
<td>-</td>
</tr>
<tr>
<td>13:20 - 13:30</td>
<td>Next steps</td>
<td>Robert Lempert</td>
</tr>
</tbody>
</table>

SOURCE: The authors.

### Table A.3. Demonstration and Feedback Workshop Agenda

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<td>Introductions</td>
<td>Robert Lempert</td>
</tr>
<tr>
<td>12:05 - 12:25</td>
<td>Decision framing recap</td>
<td>Pedro N. de Lima</td>
</tr>
<tr>
<td>12:25 - 12:55</td>
<td>Pilot RDM analysis presentation</td>
<td>Pedro N. de Lima</td>
</tr>
<tr>
<td>12:55 - 13:25</td>
<td>Breakout groups decision making exercise</td>
<td>-</td>
</tr>
<tr>
<td>13:25 - 13:55</td>
<td>Breakout groups report decisions back</td>
<td>-</td>
</tr>
<tr>
<td>13:55 - 14:00</td>
<td>Next steps</td>
<td>Jonathan Ozik</td>
</tr>
</tbody>
</table>

SOURCE: The authors.
Appendix B. Pandemic Response Decision Framing Elements

This appendix consolidates three XLRM decision-framing categories: Levers, Uncertainties, and Outcome Measures elicited during the decision-framing workshop. Workshop participants were presented with a hypothetical scenario described in Chapter 3, in which a new pandemic emerged. Then, they were asked to list three of the four elements of the XLRM framework – Policy Levers (L), Uncertain Factors (X), and Outcome Measures (M). Participants were given 30 minutes to answer the three problem-framing questions; hence, they were instructed not to discuss relationships (R) (i.e., how to model the relationships between uncertain factors, levers, and outcome measures). What follows is a consolidated list of answers pooled from three separate breakout groups and only lightly edited for clarity. Rather than a finished XLRM framing generally used for a Robust Decision Making engagement, this list contains a range of elements that can be used in multiple potential RDM studies.

Levers

*Policy Levers are actions that decision-makers can take to pursue their goals.*

**Non-pharmaceutical interventions**

- Social Distancing
- Business closures
- Work-from-home recommendations
- Masking
- Contact tracing
- Level of enforcement applied (i.e., messaging, recommendations, and mandates)
- Rules to introduce and remove sets of NPIs over time based on epidemiological metrics.

**Resource allocation strategies**

- Vaccine rollout strategy
  - Allocation formulas to prioritize disproportionally affected populations
  - Vaccine distribution prioritization may require test positivity rates to be equal across populations
- Build and sustain testing capacity
- Test site positioning
- Build Vaccination Capacity
- Make treatments available in all pharmacies
- Optimize care-setting (mainly primary care) for pandemic response
Inter-agency Coordination & Health Services

- Investment in and promotion of coordination between and within states
- Establish an incident command structure integrating multiple agencies
- Identify which administrative processes might need to be waived to procure supplies quickly
  - Flexibility in healthcare requirements (flex spaces, out-of-state staffing, etc.)
- Special emergency orders (e.g., requirements for data reporting, pre-entry or surveillance testing)
- Get funding to implement programs/strategies.
- Other supporting social welfare efforts including debt forgiveness, unemployment assistance, food assistance, etc.

Data and Information Gathering

- Standardize datasets and data reporting requirements.
- Monitor trends and make the data readily available in a clear and understandable way.
- Invest in more integrated and communicative data systems.

Communication, Public Trust, and Community Engagement

- Emergency proclamation
- Acknowledge ignorance (masking, best treatments, those most at risk, equity, in preparation for vaccine rollout)
- Public health emergency system – free up mechanisms in other lanes
- Communication strategy for disseminating guidance, make sure it's reaching vulnerable sub-populations
- Invest in informing people well ahead of knowns.
- Partnership and community engagement – also to best inform equity and effectiveness of the interventions.

Research and Analysis

- Fund/encourage specific types of research to achieve a balanced research portfolio to inform all relevant and salient pandemic response decisions
- Establish scientific advisory committees

Tiered Intervention Organization

One participant identified the following set of tiers for organizing interventions:

- Bucket 0: Gather data to help distinguish/validate mental models
- Bucket 1: Prevention
  - travel restrictions
  - skilled nursing facility
- Bucket 2: Containment
- Identify early and contain
- Isolation, quarantine

- Bucket 3: Mitigation
  - Educate people and provide information

- Bucket 4: Get Rt < 1 (Bucket 4, more aggressive than 3)
  - Suppression (COVID Zero)

- The mental model of the dominant mode of transmission guides weighting and progression among buckets
  - Japan (airborne mental model)
  - U.S. (droplets mental model)

**Uncertainties**

Uncertainties are factors outside decision-makers’ control that affect their ability to pursue their goals.

**Disease Characteristics**

- Transmissibility.
- Severity
- Natural history of the infection
- Clinical Spectrum of infection (i.e., how symptoms vary from person to person)
- Pathogen mutation rate and potential for immunity escape
- Main transmission modes (aerosol vs droplet vs vector-borne, etc.)
- Incubation period
- Latent period (if shorter than incubation, there will be asymptomatic transmission)
- Infectious period and viral kinetics (i.e., when people are most infectious)
- Changes in disease progression and severity given new variants
- Portals of exit (respiration, excretion)
- Heterogeneity in susceptibility to the disease, including age differences.
- Heterogeneity in transmission rates across settings (i.e., schools/exercise gyms/social groups)

**Intervention Effectiveness**

- Capacity to gather information/respond (testing, contact tracers, etc.)
- Data collection abilities/infrastructure
- Public health/healthcare staffing (currently low)
- Effectiveness of current treatments
- Timeline for effective treatments/vaccination
- Capacity to respond
- Supply shortages (e.g., PPE)
• people to undertake tasks
• Epidemiological and intervention time scales
• Test characteristics (sensitivity/specificity)

Social & Behavioral Response

- Uncertainty around politics and political willingness to act
  - Public support and adherence to interventions
  - Effect of media and misinformation on adherence and support for interventions
  - Information and misinformation spread
- Scientific and public beliefs about the main transmission modes
  - Complex interactions between behavior, economic outcomes, and pandemic dynamics
  - Effect of pandemic and interventions on systems such as the educational system
  - Policy and behaviors adopted in other US states and countries.
  - Level of coordination in systems and actors

Outcome Measures

Outcomes measures define the goals decision makers try to achieve in a decision problem.

Health Outcomes

• Hospitalizations
• Deaths
• Cases
• Healthcare system utilization (ICU, hospitals)

Health Outputs

• Test positivity
• Resource availability (PPE, etc.)
• Disease transmission
• Availability of tests
• Geographic distribution of epidemiological outcomes
• Test results turnaround time
• Availability and efficacy of clinical treatments
• Systems to support the distribution of treatments and testing

Economic and Social Outcomes

• Economic Costs of interventions and disease incidence
• Mental Health effects of intervention and exposure to disease burden
• Educational and developmental outcomes
• Impact of interventions on social interactions

**Equity Outcomes**

All outcomes listed above are usually not evenly distributed in the population

- Examples:
  - Vaccine distribution, regardless of healthcare coverage
  - Service availability, access to clinics and testing, test to treat
  - Considering equity means ensuring vulnerable subpopulations are not disproportionately impacted

**Behavioral Outcomes**

- Behavioral response to interventions includes:
  - Trust: Do people trust public health officials?
  - Buy-in: Do people willingly accept to do what is being proposed?
  - Compliance: Do people adhere to the interventions proposed?

**Process Measures**

Pandemic response processes should be:

- Agile: Gather information quickly.
- Appropriate (or “Pareto-efficient”): Keep policy changes in line with the current understanding / best-available science
- Stable: Minimize changes in public health (as possible), including orders, guidance and recommendations
- Transparent: the public should understand how decisions are made and why they are legitimate.
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SARS-Cov-2</td>
<td>Virus that causes the coronavirus disease 2019</td>
</tr>
<tr>
<td>COVID-19</td>
<td>coronavirus disease 2019</td>
</tr>
<tr>
<td>RDM</td>
<td>Robust Decision Making</td>
</tr>
<tr>
<td>XLRM</td>
<td>Exogenous Uncertainties (X), Policy Levers (L), Relationships (R) and Outcome Measures (M)</td>
</tr>
<tr>
<td>MORDM</td>
<td>Many-Objective Robust Decision Making</td>
</tr>
<tr>
<td>RESUME</td>
<td>Robust Epidemic Surveillance and Modeling</td>
</tr>
<tr>
<td>PIPP</td>
<td>Predictive Intelligence for Pandemic Prevention</td>
</tr>
<tr>
<td>NSF</td>
<td>National Science Foundation</td>
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<tr>
<td>CDC</td>
<td>Centers for Disease Control and Prevention</td>
</tr>
<tr>
<td>PPE</td>
<td>Personal Protective Equipment</td>
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<tr>
<td>DMDU</td>
<td>Decision Making under Deep Uncertainty</td>
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References


