

A participatory modelling approach for investigating the spread of COVID-19 in countries of the Eastern Mediterranean Region to support public health decision-making

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ABSTRACT

Early on in the COVID-19 pandemic, the WHO Eastern Mediterranean Regional Office recognised the importance of epidemiological modelling to forecast the progression of the COVID-19 pandemic to support decisions guiding the implementation of response measures. We established a modelling support team to facilitate the application of epidemiological modelling analyses in the Eastern Mediterranean Region (EMR) countries. Here, we present an innovative, stepwise approach to participatory modelling of the COVID-19 pandemic that engaged decision-makers and public health professionals from countries throughout all stages of the modelling process. Our approach consisted of first identifying the relevant policy questions, collecting country-specific data and interpreting model findings from a decision-maker's perspective, as well as communicating model uncertainty. We used a simple modelling methodology that was adaptable to the shortage of epidemiological data, and the limited modelling capacity, in our region. We discuss the benefits of using models to produce rapid decision-making guidance for COVID-19 control in the WHO EMR, as well as challenges that we have experienced regarding conveying uncertainty associated with model results, synthesising and comparing results across multiple modelling approaches, and modelling fragile and conflict-affected states.

INTRODUCTION

In January 2020, a cluster of patients with pneumonia of unknown cause was reported in Wuhan, China; the disease, later named COVID-19, was found to be due to a novel coronavirus, SARS-CoV-2. The disease spread worldwide and was declared a pandemic by the WHO on 11 March 2020.¹ In the Eastern Mediterranean Region

Summary box

- Early on in the SARS-CoV-2 pandemic, some countries from the Eastern Mediterranean Region requested technical support from the WHO for mathematical epidemiological modelling to help guide the implementation of public health and social measures.
- We designed a participatory process to develop rapid modelling analyses that are tailored to the COVID-19 epidemic situation in each country. Eleven countries in the region engaged in this process and we document examples of how the results were used to inform policy decisions for COVID-19 control.
- Challenges involved in this participatory modelling included analysing epidemics in countries with limited surveillance data, especially in those suffering from armed conflict and political instability.
- The approach demonstrates how rapid technical modelling support can be applied to engage policy makers and to develop timely guidance for public health decision making in an emergency response to a novel pandemic.

(EMR), the first cases were detected in the United Arab Emirates on 29 January 2020. By 15 January 2021, the 22 countries and territories of the Region have been affected with more than 4.5 million reported cases and almost 130 000 reported deaths.² However, the true burden of COVID-19 in the Region is not fully measured due to various factors including limiting testing and inadequate surveillance systems available in many countries. The number of cases of COVID-19, and attributable deaths, is under-reported to an unknown extent. Several EMR countries suffer from economic insecurity, armed conflict and

political instability, and have limited capacity for public health surveillance.³

Since the beginning of the pandemic, public health authorities have faced an urgent need to make decisions regarding various actions to mitigate the spread of the virus and the associated pressure on health-care systems. Early detection and isolation of cases, contact tracing and quarantine of contacts are critical to prevent further spread of the virus and reduce morbidity and mortality.^{4,5} Also, early in the outbreak, many countries introduced additional public health and social measures (PHSM), which include intervention strategies such as movement restrictions, closure of schools and businesses, and international travel restrictions to slow down disease spread and relieve some pressure on clinical care services.⁶ By mid-March 2020, all countries in the EMR had applied some form of PHSM. Not only are these measures difficult to implement in some countries of the region, but they are also accompanied by considerable social and economic costs. Thus, decisions to tighten, loosen or reinstate PHSM should be based on local epidemiological data, risk assessments⁷ and available scientific evidence.⁸

APPLYING MATHEMATICAL MODELS TO SUPPORT DECISION-MAKING IN THE COVID-19 PANDEMIC

Mathematical epidemiological models are useful for informing such decisions through exploring and understanding the consequences of a variety of plausible scenarios regarding assumptions about virus and disease characteristics, health system capacity, and the timing and strength of PHSM.^{9–11} We provide a background to how epidemiological models have been applied to analysing the COVID-19 pandemic in online supplemental text A1 in the appendices. In summary, mathematical models allow prediction and comparison of key epidemiological outcomes such as the daily incidence of infections (including severe infections that require hospitalisation and intensive care) and deaths. There is considerable uncertainty associated with these predictions, particularly as COVID-19 is a novel viral disease in humans, for which the evidence on transmission and clinical outcomes continues to evolve, and as such many of the parameters and processes that govern its spread and clinical outcomes are unknown or poorly quantified.^{10–12} Moreover, models make simplifying assumptions in their representation of reality, and they evolve and adapt over time with the emergence of new data and evidence.¹² Nonetheless, the qualitative behaviour of models can effectively address certain questions of current importance to policy-makers. For example, models can compare different scenarios that represent alternative PHSM strategies and give insight into their relative benefits,^{10, 13} such as flattening the epidemic curve and reducing the expected burden on the health-care system.¹⁴ Models can warn about future waves of

infection, subject to their assumptions about infection, reinfection and immunity.¹⁵ Importantly, modellers need to work closely with decision-makers and the media to ensure that model predictions are interpreted and used appropriately, that the associated uncertainty is clearly communicated¹² and that the context and motivation of the developers and users are transparent.¹⁰ This collaboration is also important for collection of model inputs as the reliability of any prediction is conditional to the quality of the epidemiological data feeding the model. Moreover, while a model is a useful tool for supporting decision-making, its predictions should be interpreted across a realm of other tools and data sources.

PARTICIPATORY APPROACH TO MODELLING THE COVID-19 PANDEMIC IN THE EMR

Public health officials in EMR countries noted how mathematical epidemiological models were informing public health decisions in the countries that were hit earlier in the pandemic.^{16, 17} As a result, some of them have expressed an interest in receiving technical support from WHO for mathematical modelling to interpret the potential epidemiological spread of the outbreak, given different PHSM scenarios. Accordingly, the WHO Eastern Mediterranean Regional office (EMRO) established a modelling support team in mid-March as part of the Information Management pillar in the COVID-19 Incident Management Support Team.¹⁸ This is the first time the WHO Regional Office used modelling as a tool in an ongoing outbreak response. Here, we present an innovative approach that was developed by the EMRO modelling support team to conduct participatory modelling analyses together with public health professionals from the EMR to support decision-making.

The primary objective of the modelling support team was to address the imminent decision-making needs faced by policy-makers. Another objective was to provide training on mathematical epidemiological modelling, including the underlying concepts and methods, to promote awareness of how models work and how they can be used effectively and to work towards building technical capacity for mathematical modelling in the EMR.

A participatory approach was adopted to conduct country-specific modelling analyses that were relevant to the PHSM being considered for the country. As part of this approach, policy-makers from the Ministries of Health in the countries and WHO country offices (WCOs) were actively involved throughout all stages of the modelling process.^{13, 19, 20} The WHO EMRO modelling support team also worked with the WHO Headquarters, researchers from academia and other United Nations (UN) agencies to investigate different modelling approaches, help interpret model results and guide the analysis of policy-relevant questions (see online supplemental figure A3 in the appendices). Participatory modelling can facilitate the translation of model findings into decision-making in a number of ways. First, it can guide the modelling

analysis to identify and address questions that are relevant and important to public health in the country. It can also encourage shared learning among researchers, modellers and policy-makers, and foster common understanding and expectations.¹⁹ Importantly, the involvement of within-country analysts and policy-makers builds trust, ownership and support,^{19 20} meaning that the findings of the analyses will be more likely to be considered in decision-making.

POLICY QUESTIONS POSED BY POLICY-MAKERS IN EMR

After consulting with policy-makers from countries, by the end of March 2020, the EMRO modelling support team identified the most urgent questions to address through modelling exercises: (1) How many infections and deaths are expected at different times? (2) What are the expected healthcare system requirements? (3) What is the effect of PHSM on the spread of the epidemic? To be suitable for supporting rapid decision-making in countries in the EMR, many of which are low/middle-income countries, the modelling tools used needed to be readily adaptable to country-specific settings and PHSM policies, with data inputs swiftly attainable and requiring low computational resources. It was also necessary to use an interpretable modelling approach that could be readily communicated in non-technical terms to participants from a variety of disciplines.

APPLICATION OF THE COMO MODEL IN THE EMR

The team found that the COVID-19 International Modelling (CoMo) model developed by the CoMo Consortium²¹ offered a user-friendly interface to modelling impacts of PHSM on the time trajectories of infections (including severe infections requiring hospitalisation and intensive care) and deaths. The CoMo model was able to address the questions posed by policy-makers in the region, had the flexibility to be adapted to the regional context and had a computationally efficient online application that allowed the model to run quickly on large populations.

The CoMo model²¹ is an age-dependent deterministic Susceptible–Exposed–Infectious–Recovered model that predicts daily incidence of COVID-19 infections in the population under different assumptions about PHSM. Details of the CoMo methodology are provided in online supplemental text A1 in the appendices. In summary, the model considers five levels of infection severity: asymptomatic infections, symptomatic infections, and infections requiring hospitalisation, intensive care treatment and ventilated intensive care treatment. Infection severity and associated mortality are age-dependent, in that the proportion of infected individuals requiring hospitalisation, and the proportion that die, varies with age. The CoMo model incorporates a hospital submodel that indicates when hospital treatment requirements, including treatment in hospital beds, intensive care units and ventilators, exceed the capacity of the country's healthcare system.

The CoMo model incorporates an explicit representation of the PHSM that have been commonly used to mitigate the spread of COVID-19. The model considers PHSM that target infected individuals, including self-isolation of symptomatic individuals and self-quarantine of members of their household, screening of the contacts of individuals with a positive diagnostic test result and mass testing. The model also considers PHSM that aim to limit transmission throughout the wider population, including school closure, workplace closure, physical distancing measures, border closure, shielding elderly individuals, handwashing and mask-wearing. For each intervention, the user provides inputs about the coverage, defined as the proportion of the total population to which the intervention applies. The user also inputs the intervention timing and duration, and the adherence of the population to the intervention. These coverage and adherence parameters act on age-specific social contact rates in home, work, school and other community environments, which are estimated in the model using the country-specific contact matrices developed by Prem *et al.*²² A useful feature of the CoMo model is that it allows the coverage of each intervention to vary over time, meaning that the intervention can have a stronger effect over some time periods and a weaker effect over other time periods. We have used this feature in applying the model to EMR countries to represent relaxations of PHSM (such as during Eid and Ramadan periods) and strengthening of measures in response to resurgences in infections.

PARTICIPATORY MODELLING PROCESS

The EMRO modelling support team, together with the CoMo Consortium, has been adapting the CoMo model to investigate COVID-19 spread dynamics in countries in the EMR, as well as interpreting the results and conveying the models' caveats to the countries. Throughout this process, the team has assisted countries in identifying data sources, gathering country-specific data, documenting model outputs and preparing policy briefs. The team supports capacity building by delivering training and demonstrations of the models and the online tool. Establishing participatory collaborations with EMR countries to adapt and run the CoMo model involved the following stepwise approach:

1. *Introduce modelling approach:* The EMRO modelling support team introduces the modelling approach to the interested countries using an audiovisual presentation that provides a non-technical overview of the CoMo model, including the main inputs, outputs and limitations. This is supported by social media videos in three regional languages.^{23–25} The introductory sessions and the videos convey basic information about epidemiological models and the uncertainty about model parameters and structure.
2. *Assemble collaborating team:* A team of core collaborators that will participate in the modelling analysis is assem-

bled. This includes public health professionals from the country Ministry of Health and the WCO as well as the EMRO modelling support team.

3. *Collect model input data:* Once the collaborating team embarks on a collaboration, the data collection template and a reference manual describing the model parameters and their definitions are shared. The country Ministry of Health and the WCO are supported during the collection of country-specific model parameters by convening data collection webinars and sharing data sources.
4. *Review input data:* The EMRO modelling support team corroborates the data inputs by cross-checking with published literature and the country Ministry of Health and the WCO. The team also cross-checks the assumptions being made about the strength and timing of the PHSM implemented in the country with Google mobility reports²⁶ and Oxford government response tracker.²⁷ Any discrepancies are discussed with collaborators from the country to develop a common understanding and agree on any revisions.
5. *Conduct initial modelling analysis:* Modellers from the EMRO modelling support team and the country conduct an initial modelling analysis to produce preliminary results. The analysis employs a scenario-based approach that develops customised scenarios which compare different PHSM implementation strategies based on the questions posed by the countries. The team drafts a technical report containing details about model inputs, methods, results and limitations that is then shared with country Ministry of Health and the WCO.
6. *Review initial results:* The country Ministry of Health and the WCO review the technical report and discuss with the EMRO modelling support team any modifications or updates required.
7. *Update modelling analysis:* The EMRO modelling support team updates the modelling analysis and produces an updated technical report which is shared with the country Ministry of Health and the WCO.
8. *Summarise policy implications:* The EMRO modelling support team prepares a non-technical audiovisual presentation together with a policy brief document that targets a wide public health audience and interprets the main findings of the analysis from the perspective of decision-making, as well as conveying the uncertainty and limitations.
9. *Continue collaboration:* Engagement with countries continues as required to update the modelling analysis according to the progression of the COVID-19 outbreak and the control strategies under consideration in the country.

The components of this participatory modelling approach, including participants, resource requirements and methodological approaches, are summarised in online supplemental table A1 and figure A3 in the appendices. We have evaluated our experience of implementing the above nine-step process to identify benefits

and limitations, and provide recommendations for the continued use of this approach (online supplemental table A2 in the appendices).

PROGRESS TO DATE

As of mid-January 2021, 11 countries, namely, Afghanistan, Djibouti, Egypt, Iraq, Jordan, Lebanon, occupied Palestinian territories (oPt), Pakistan, Syria, Tunisia and Yemen, have been engaged in collaborative modelling with EMRO. Of these, seven, namely, Afghanistan, Jordan, Lebanon, Pakistan, Egypt, oPt and Tunisia, had reached stage 8 of the above process and disseminated the results of the modelling analyses and policy implications to the decision-makers. Scientific committees and decision-makers in some of those countries are consulting the model's projections, in conjunction with the epidemiological data and other data sources, when examining current policies in place and weighing possible options for instating or loosening certain measures. For instance, Tunisia's epidemiologists are exploring options of immediate or gradual release of physical distancing and working from home measures.²⁸ The EMRO modelling support team is currently in the process of documenting examples where model results have already been incorporated into policy. One example is the school opening strategies, such as the cyclical school opening strategy adopted in oPt.²⁹ Another example is the implementation of 1-day lockdown per week and a daily night-time curfew in addition to keeping schools online till the end of the semester in Jordan.³⁰ Investigating testing strategies and possibilities of under-reporting with the modelling tool is also currently being explored in some countries.

CHALLENGES

There are a number of barriers to effective and widespread use of models in the EMR, such as the insufficient availability of national data and limited national modelling capacity. There is considerable uncertainty associated with modelling the dynamics of novel viruses,^{10 11} and interpreting the results can be challenging given the general limitations of the models and the input data on which they are based (online supplemental text A1 and table A2 in the appendices). The EMRO modelling support team has tackled these issues by communicating throughout all stages of the modelling collaboration the expectations about the appropriate uses and limitations of models. The social media videos that were developed by the team are presented in Arabic, English and French, and describe the uncertainty associated with epidemiological models of COVID-19 and how model results can be interpreted to guide decision-making.²³⁻²⁵ These videos were disseminated on different platforms and at the time of writing had received 25 359 views across all platforms. The team also encourages national capacity building by providing training on the modelling approach and caveats, as well as on using the online software and the interpretation of results. These challenges can be further

addressed through encouraging active engagement in modelling as a part of public health decision-making as well as strengthening the local systems for epidemiological surveillance and data storage.

At present, several modelling analyses of the COVID-19 pandemic have been conducted for EMR countries by different international research groups, each using different modelling approaches and making different assumptions about viral transmissibility and severity, and the implementation of PHSM.^{31–35} This can lead to discordant sets of results and guidance being presented to policy-makers, which can be difficult to assimilate, is confusing and can potentially lead to a distrust, and loss of interest, in models. A challenge for the modelling community lies in systematically comparing and synthesising results provided by different models to provide clear and consistent guidance to decision-makers.³⁶ Model comparison initiatives that are currently reviewing the results of multiple COVID-19 epidemiological models are a promising step towards achieving this goal.^{37–38} The EMRO modelling support team is involved in these activities through an international network of collaborations with academic institutions and other UN agencies (online supplemental figure A3 of the appendices).

The socioeconomic and geopolitical situation in the EMR is another unique challenge, not only for implementing PHSM but also for modelling the COVID-19 outbreak. More than half its countries are currently suffering from armed conflict and political instability.³⁹ In addition, it is estimated that out of the 600 million people living in the region, 13 million are internally displaced, 12 million are refugees⁴⁰ and 46 million are low-income labour migrants.⁴¹ These populations often reside in overcrowded spaces with poor living conditions, such as camps or camp-like settings, where it can be difficult to apply certain public health measures, such as physical distancing and self isolation. Basic adherence to personal protective measures (such as handwashing) is problematic as well due a lack of basic sanitation services. It has been estimated that the burden of COVID-19, in terms of numbers of infections and attributable mortality, has been greatly under-reported in conflict-affected countries in the EMR.^{42–44} A number of approaches for modelling COVID-19 dynamics in internally displaced people (IDPs) and refugee camps are being developed,⁴⁵ and the EMRO modelling support team is investigating the application of such approaches to the region.

CONCLUSION

Mathematical epidemiological models offer a whole system approach to analysing the COVID-19 pandemic and can assist countries with the multifaceted aspects of public health planning and decision-making. The EMRO modelling support team is a new initiative for the WHO, and it has developed a participatory modelling approach for the EMR to undertake analyses that are tailored to the context of the countries in the region. The strength

of the approach lies first in the rapid and active engagement of public health policy-makers with epidemiologists and modellers from countries within the region. This was achieved through coordinating with other WHO regional offices, EMR WCOs and WHO headquarters. Second, the team's activities continue to benefit from establishing collaborations with academic and other UN institutions, which has provided access to technical expertise covering a wide range of modelling approaches. Through this participatory approach, the model will continue to be revised based on prevailing decision-making needs, such as the recent added function of investigating various scenarios of COVID-19 vaccine introduction. The quality of model results, however, depends on the quality of the epidemiological data that serve as model inputs, and model projections are not a replacement for a lack of comprehensive surveillance and experimental evidence. The challenges associated with mathematical modelling are pronounced in the EMR, where several member states do not have sufficient resources and technical capacity for collecting, processing and modelling epidemiological data. Data unavailability and poor quality, especially in conflict-affected countries,⁴⁶ will increase the uncertainty associated with model findings. The participatory modelling approach, webinars, social media videos, technical reports and policy briefs are steps towards building capacity for mathematical modelling in EMR, raising the awareness of the use of mathematical models, their benefits and limitations. By continuing active engagement with country collaborators, and the international modelling community, we will continue to strengthen epidemiological surveillance and modelling analysis for public health decision-making in the region.

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APPENDICES

“A participatory modelling approach for investigating the spread of COVID-19 in countries of the Eastern Mediterranean Region to support public health decision-making”

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Text A1: Applications of Susceptible-Exposed-Infectious-Recovered (SEIR) models to guide policy making throughout the COVID-19 pandemic

Mathematical epidemiological models have been widely applied throughout the COVID-19 pandemic to provide quantitative and reproducible *in silico* simulation of the epidemiological dynamics of COVID-19. They provide a holistic approach to modelling the epidemiological system, considering multiple dynamic processes that interact to drive virus transmission patterns. For example, they model processes of viral transmission in the human population, utilising data describing expected rates of human-to-human contact in different environments (such as workplace, school and home environments) and different geographic regions. They also include data on the characteristics of the COVID-19 virus such as its transmissibility and the duration of the viral incubation period, as well as the expected rates of severe infections and deaths. They can include information about how these processes vary across different demographic variables and vulnerability characteristics. Models combine these epidemiological processes and describe their highly non-linear interactions, which are difficult to understand using only intuition (1). Models have been applied globally throughout the pandemic to guide policy makers about possible future trajectories of COVID-19 infections and deaths, the consequent demands on healthcare systems, and how these can be influenced by the implementation of various public health and social measures (PHSM).

1.1 The SEIR model

Many epidemiological models of COVID-19, including the CoMo model, are based on mechanistic Susceptible-Exposed-Infectious-Recovered (SEIR) modelling approaches (2) that model the mechanisms of viral transmission and the progression of the infection in individuals who have contracted the virus. In its simplest form, the SEIR model subdivides the human population into four classes of individuals (Figure A1): (i) Susceptible individuals, meaning those who are not currently infected and can potentially contract the infection upon making an infectious contact; (ii) Exposed individuals, meaning those who have become infected with a virus that is still undergoing incubation; (iii) Infectious individuals, meaning those who are infected with a virus that has completed the incubation phase and can potentially cause clinical symptoms; (iv) Recovered individuals, meaning those who have recovered from the infection and are no longer infected. The rates of transition between each of the four classes are defined by parameters that are estimated based on observations of viral spread and infection progression in the human population. Importantly, the rate at which Susceptible individuals become infected is proportional to the number of individuals who are Infectious (Figure A1), thus infections grow exponentially in the initial phase of the epidemic. The mathematical model tracks the temporal evolution of the number of individuals in each of the Susceptible, Exposed, Infectious and Recovered classes using a series of differential equations.

The SEIR framework can be modified to include several types of additional structure that is relevant to the COVID-19 epidemic. For example, the CoMo model subdivides the population according to age (Figure A2), and allows patterns of human-to-human contact to vary with age as well as environmental setting. Age-dependent contact rates are specified for four different

environments, including home, school, workplace and other environments, where the “other” environment type summarizes all contacts outside the home that are not workplace or school contacts. The CoMo model allows the impacts of specific PHSM on different contact rates to be explored, including those that affect specific environments such as the closure of schools or workplaces, as well as wider lockdowns that reduce contacts in all non-home environments. Additionally, the model can consider reductions in contacts in individuals who are self-isolating or who are in quarantine. It is important to note that human mobility, and the spatial and geographic dimensions of human contact patterns, are also an important determinant of the spread of COVID-19 infections. At present, the CoMo model does not include spatial structure, and therefore does not represent variation in contact rates and viral transmission according to the spatial proximity of individuals, or across different geographic regions. There are other SEIR models of the COVID-19 pandemic that have been applied to Lower and Middle Income Countries (LMICs) that do explicitly model spatial structure and human movement (3).

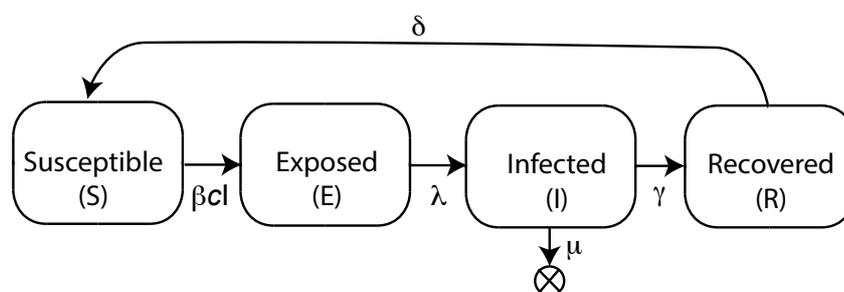


Figure A1. A simple SEIR model. Susceptible individuals contract the infection and become Exposed at a rate proportional to the number of infected individuals in the population, I , the average number of daily contacts, c , and the probability of viral transmission given an infectious contact, β . Exposed individuals enter the Infected class at a rate λ , and infected individuals either recover at a rate γ or die from the disease at a rate μ . Recovered individuals lose their immunity to reinfection at a rate δ .

The CoMo model also incorporates a hospital sub-model (Figure A2) that subdivides infectious individuals according to hospital treatment requirements, and represents an age-dependent increase in the likelihood of severe infections that require specialized hospital treatment. This allows projection of the expected burden on the healthcare system. As we learn more about the COVID-19 virus, models can be further refined to represent additional mechanisms and structure. For example, recent updates to the CoMo model consider varying degrees of immunity to re-infection with COVID-19 in recovered individuals and how this depends on the decay of COVID-19 antibodies over time (4). Models may also consider how the disease burden is impacted by the prevalence of other health conditions that can increase vulnerability to severe disease outcomes.

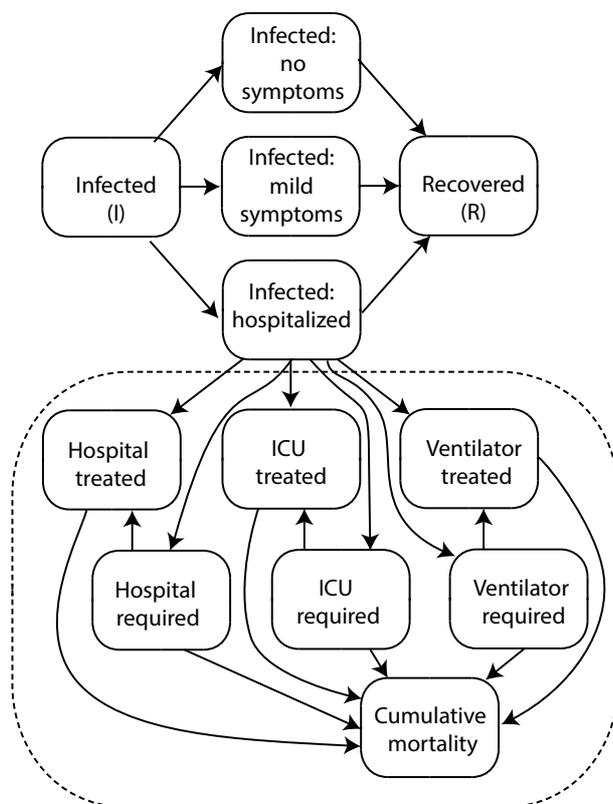


Figure A2. The CoMo model incorporates a hospital submodel (enclosed by the dashed line). The model subdivides the Infected individuals into those who experience no symptoms, mild symptoms, or a level of severity that requires hospitalized treatment. Hospitalized individuals are categorized according to the type of treatment they require (hospital, ICU, or ICU and Ventilator treatment) and whether or not they are receiving the required treatment. When the hospital reaches its capacity for a given treatment type, individuals who require a given treatment but do not receive treatment are placed in either the “Hospital required”, “ICU required”, or “Ventilator required” classes according to the type of treatment required. These individuals can move into the “Hospital treated”, “ICU treated” or “Ventilator treated” classes if resources become available. COVID-19 attributable mortality occurs only in individuals with an infection severity that requires either hospital, ICU or ventilator treatment.

Studies that have conducted validation analyses of the CoMo model by comparing model predictions to the future trajectory of reported COVID-19 cases and attributable deaths have shown encouraging results, with the timing of the epidemic peak being predicted within an accuracy of 2 weeks (5). Precise quantitative forecasting of future disease outcomes is not, however, the primary focus of the CoMo model. In the following section, we describe recommendations related to appropriate uses of epidemiological models in guiding public health decision making for managing the COVID-19 pandemic.

1.2. Appropriate use of models to guide policy-making

The COVID-19 pandemic has generated a heightened interest in mathematical epidemiological models across many sectors of society as policy-makers and the public seek clarity around the future implications of this novel virus. Mathematical modelling has played a prominent role in policy making throughout the pandemic, and this novel focus on modelling, together with the novelty of the pandemic itself, has led at times to confusion and misunderstanding about how to use models appropriately and effectively to guide public health decision making. The scientific modelling community has an important role to play in guiding public health managers, politicians and the wider public about how to interpret and apply the results of models. Since the beginning of the pandemic several modelling research groups have published guidance that summarizes and reviews, in non-technical language, key underlying principles for using mathematical models to guide policy making (1,6,7).

An important and widely emphasized principle is that model predictions need to be accompanied by a full and transparent assessment of the associated *uncertainty* (1,6–9). Predictions need to be presented as range of values describing the uncertainty interval, namely the confidence or credible interval (CI), rather than a single numeric value. CIs only provide estimates of a part of the uncertainty, however, and do not capture all uncertain aspects, because all models are a simplified representation of reality and are based on assumptions. It is therefore important that statements about uncertainty include a full articulation and assessment of model assumptions, including how these may impact model predictions, and that areas of ignorance are acknowledged.

Moreover, the validity of model estimates depends entirely on the quality of the epidemiological data used to construct and parameterize the model. In the case of COVID-19, there is considerable uncertainty in reported epidemic trajectories due to a multitude of factors such as biases in the sets of individuals who are tested, under-reporting of cases and deaths, and uncertainty in laboratory assays and diagnoses. Key aspects of the epidemiology of COVID-19 remain uncertain, including the extent and duration of immunity following infection, the extent and transmissibility of asymptomatic infections, and patterns of human-to-human contacts across different populations and regions (1).

Thus, while public health managers seek accurate numbers about future COVID-19 infection rates, hospitalizations and deaths, models cannot provide predictions with this level of certainty. Models are not crystal balls (10), and it is not appropriate to use models to provide a single precise forecast of future epidemiological outcomes (7). Models are more effective when used to assess relative impacts across several sets of predictions (7). For example *scenario-based* modelling approaches present results across multiple scenarios that make different explicit assumptions about parameters and processes of interest (11,12), and draw insights from the qualitative as well as quantitative differences in predictions across different scenarios. From the perspective of public health policy making, it is useful to focus on the relative impacts of different PHSM, and to include an assessment of the scale of the expected burden on the healthcare system (7).

Quantitative predictions are typically only useful in short term forecasts. An important aspect of assessing model validity and uncertainty involves follow-up

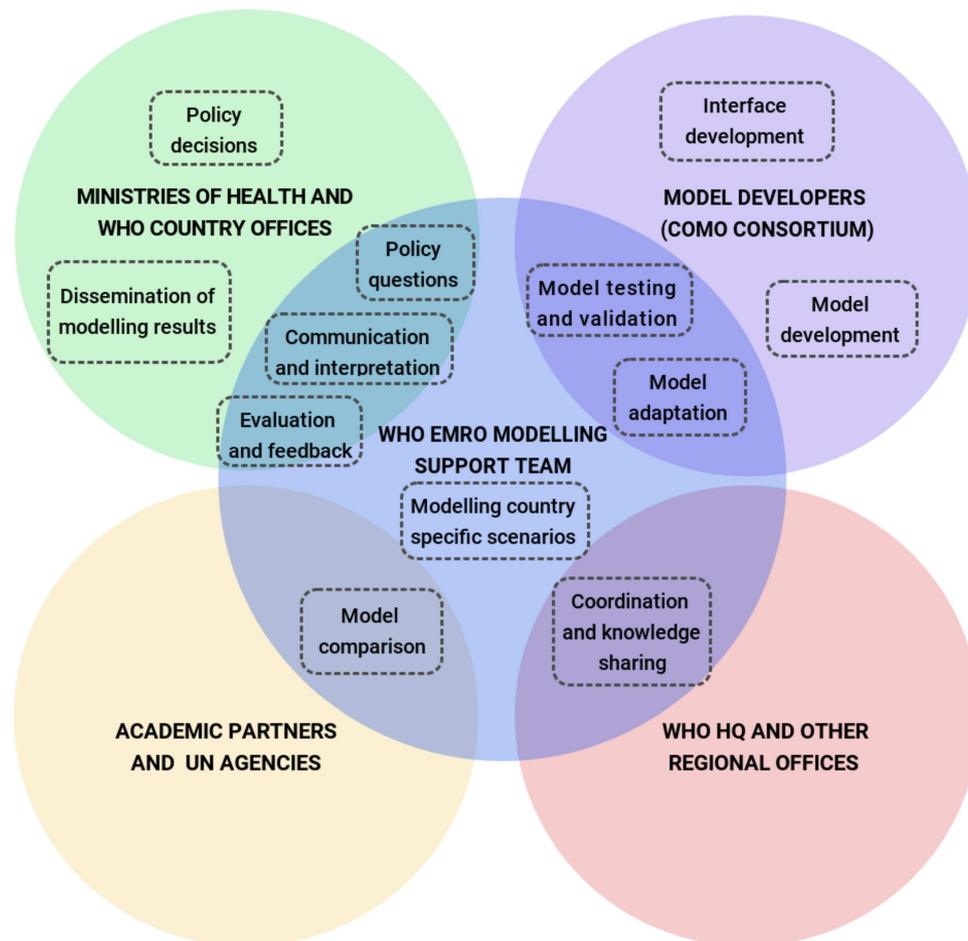
analyses to compare short term predictions to observations as they become available. It is critical that modelling analyses are *reproducible* so that predictions made at different times can be regenerated and assessed.

There can be a tendency to favour complex models over simpler approaches, and to assume that greater complexity leads to more realistic and robust predictions. This will not be the case, however, if complex models misrepresent or omit key biological aspects (1,7). It is therefore important that model choice and design incorporates an assessment of the *trade-off between simplicity and complexity*. This trade-off depends on the availability of data to support the development of a more complex model. Modellers need to acknowledge issues associated with parameter identifiability, and recognize that it is more difficult to infer parameters, and to identify errors, for complex models than for simpler models. Moreover, it is beneficial to use modelling approaches that are *interpretable* to both analysts and end users, as this allows an assessment of how model results are related to the choice of questions addressed, the inputs used, and the assumptions made (6). This feedback is valuable to adapting and improving subsequent modelling analyses, and continuing to guide decision-making.

Finally, it is important that modelling analyses are accompanied by a *description of the context* in which the analyses were conducted, including the intended purpose of the analyses, and the background and motivation of the model developers, analysts and stakeholders. The choice of modelling approach and the design of analyses is never neutral (6), and can greatly influence the results and conclusions. Analysts therefore need to provide an explicit statement of these biases and motivations. Scientists need to work with politicians, journalists and the media to ensure that model results are not politicized, and reports of model predictions are couched in appropriate statements about context, the key caveats and uncertainty.

Table A1: Summary of the methodological approach, including participants and resource requirements, for the participatory modelling analyses conducted by the WHO EMRO modelling support team.

Participants	Resources required	Methods	
		Considerations in choosing the modelling approach	Guiding principles for modelling analysis
<ul style="list-style-type: none"> Ministry of Health in Member States WHO focal points Technical modellers Surveillance officers Epidemiologists Communication and Policy experts 	<ul style="list-style-type: none"> Software application for implementing epidemiological modelling analysis that is: <ol style="list-style-type: none"> computationally efficient user-friendly reproducible Additional mathematical and statistical software for analysis and visualization of model results e.g. R, python. Software for producing scientific presentations, reports and publications e.g. MS Office, Reference Manager Software for telecommunication support e.g. Cisco Webex Access to WHO and publicly available databases, including WHO dashboards, GIS databases, Google mobility databases and academic research databases. 	<ul style="list-style-type: none"> Timely availability for immediate application Open source, user-friendly software application Access to technical support from model developers Model and software is actively developed and maintained Model is adaptable to LMIC settings Access to an active, collaborative consortium of model users and developers Modelling approach is transparent and interpretable to users from a wide range of professional backgrounds. 	<p>We follow published scientific advice summarized in Text A1 for applying mathematical models to analyzing the epidemiological dynamics of COVID-19. In summary this advice recommends:</p> <ul style="list-style-type: none"> full and transparent assessment of model uncertainty present results for several equally plausible scenarios all results must be reproducible assessment of tradeoffs between simplicity and complexity use an interpretable modelling approach and discuss results in terms of assumptions and limitations. Provide a description of the context and motivations for conducting the modelling analyses

Figure A3: Participatory modelling approach structure and participants

Process and results	Evaluation questions	Summary of experience
<p>6. Review initial results</p> <p>7. Update modelling analysis</p>	<ul style="list-style-type: none"> - Can modelling results be interpreted in the light of uncertainties around model inputs and model limitations? - How does the modelling team plan to update the modelling analysis? 	<ul style="list-style-type: none"> - Model results interpretation can be challenging given the limitations of the models and the quality of the input data - Continuous communication is needed to clearly interpret model results and convey models limitations and caveats - Models need to be regularly updated (e.g. monthly) to produce short-term forecasts - It is important to conduct regular literature searches to guide updating model inputs and/or structure - Updating model parameters should be after developing a common understanding of model's main findings and be subjected to any changes in disease dynamics and/or the implementation of PHSM in real life. - Timely to respond to pressing policy questions (e.g. different school re-opening strategies)
<p>8. Summarise policy implications</p> <p>9. Continue collaboration</p>	<ul style="list-style-type: none"> - Are the policy implications clearly stated and can they be translated into actionable decisions? - What are the key drivers to continue collaboration? 	<ul style="list-style-type: none"> - Policy implications should be clearly and concisely summarised in plain language and target a wide range of backgrounds - The trust and ownership established through the participatory approach facilitates the translation of model results and their policy implications to decisions - Continuing collaboration builds capacity for epidemiological modelling in the region - The participatory approach encourages continued involvement and collaboration

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