Toward a decision support system for COVID-19 vaccine allocation inside countries*

Hossein Baharmand[1][0000−0003−3495−3988], Burcu Balcik[2][0000−0002−3575−1846], Lise Boey[3][0000−0001−9623−4482], Catherine Decouttere[3][0000−0003−4726−1729], Ross Phillips[4][0000−0002−1920−4658], Naima Saeed[1][0000−0002−9748−3947], and Nico Vandaele[3][0000−0001−7687−7376]

[1] School of Business and Law, University of Agder, Norway
{hossein.baharmand,naima.saeed}@uia.no
[2] Ozyegin University, Istanbul, Turkey
burcu.balcik@ozyegin.edu.tr
[3] KU Leuven, Belgium
{catherine.decouttere,nico.vandaele,lise.boey}@kuleuven.be
[4] Institute of Transport Economics, Norway
ross.phillips@toi.no

Abstract. The distribution of COVID-19 vaccines has proved to be a challenging task for public health authorities in many countries. Among several decisions involved in the task, allocating limited available vaccines to administration points is indeed critical. However, the operation management literature lacks evidence-based mathematical models that could support effective, efficient, sustainable and equitable vaccine allocation decision. This paper develops the fundamentals of a decision support system for COVID-19 vaccine allocation inside countries. The proposed DSS intends to support public health authorities in real-time by illustrating possible vaccine alternatives. The system could also inform and support other actors in the COVID19 distribution for planning and collaboration. Two illustrative cases for the COVID-19 vaccine allocation have been investigated to highlight potential benefits of our methodology.

Keywords: COVID-19, Vaccine allocation, Public health responders

1 Introduction

Several reports indicate that COVID-19 vaccines distribution has proved to be a challenging task for public health authorities in many countries (e.g., Logmore [19]). When COVID-19 vaccines arrive at a country's main entry point, public health authorities have to make critical logistics decisions to deliver vaccines to administration points. Such decisions could be long-term (e.g., where to locate storage facilities) as well as mid- and short-term (e.g., how many vaccines to be

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allocated to facilities, and how to transport vaccines to corresponding locations) [20].

Recent surveys indicate that effectiveness, efficiency, sustainability, and equity are important objectives for critical logistics decisions in vaccine distribution [11]. Here, by effectiveness, research refers to maximising the impact of vaccination by ensuring that delivered vaccines meet the vaccination demands. The efficiency objective concerns with reducing total logistics costs such as storage and transportation costs. The sustainability objective relates to reducing the footprint of the logistics. Finally, the equity objective reflects ensures that the focus is on prioritised and vulnerable groups while meeting overall demands.

Majority of operations management research on vaccine distribution focuses on proposing mathematical models to support public health authorities [12]. However, three research gaps could be observed. First, research to support allocating vaccines in the presence of different priority groups, multiple vaccines with distinct features, and variety capacity constraints is scant. The literature has mainly focused on developing mathematical models to support strategic decisions in vaccine distribution such as locating vaccine storage facilities or locating mobile vaccine administration units (cf. Section 2). Second, To the best of our knowledge, there is no study that seeks to simultaneously balance the four abovementioned objectives for vaccine allocation. Recent surveys (e.g., De Boeck et al. [11]) show that few studies have considered the equity objective in their models although it is a critical objective in the vaccine allocation [2]. Third, few studies propose evidence-based mathematical models (i.e., models that have been informed by insights or evidence from practice or have been validated by data from real cases [5]). In the absence of evidence-based models, public health authorities are often reluctant to use research findings for vaccine allocation in practice.

Our research aims to address the three abovementioned gaps. It seeks to answer: *how can we support public health authorities for COVID-19 vaccine allocation?* Our ultimate objective is to develop an intuitive web-based decision support system (DSS). A typical DSS for logistics problems with multiple objectives and different decision-makers (DMs) can consist of four components as illustrated in Figure 1. Our study contributes to the first DSS component by developing an evidence-based mathematical model (through a mixed-method approach). Our model balances effectiveness, efficiency, sustainability and equity objectives for COVID-19 vaccine allocation.

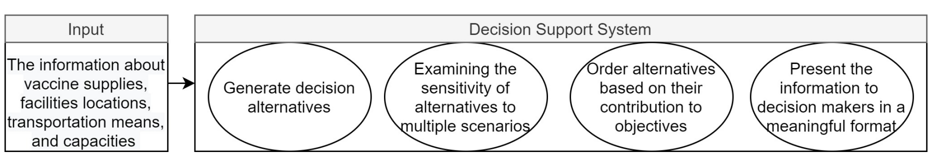

Fig. 1. Proposed DSS adapted from Baharmand et al. [5]

We acknowledge that such a DSS should consider the perspectives of stakeholders for the vaccine distribution network such as health ministries, logistics service providers, hospitals, pharmacies, and others [13]. That said, in this paper, we intend to (i) position our contribution within the existing literature (ii) describe the methodology for developing the system (iii) share an initial illustrative example, and (iv) draft a roadmap for future research on this subject.

The rest of the paper is organised as follows. Section 2 describes the background on DSS for vaccines distribution. Section 3 presents the proposed methodology. Section 4 includes primary results and discussion. Section 5 concludes the paper and outlines future work.

2 Background

2.1 In-country vaccine distribution network

The design of an in-country vaccine distribution network is a complex socio-technical problem (i.e, it includes both human and technical factors) [1, 8]. In the design of vaccine distribution network, strategic and tactical decisions are of high importance [10]. These decisions could be investigated from a global (from manufacturer to the countries), in-country (from main entry points to administration centres), or integrated perspective (comprising both global and in-country). Figure 2 shows an example of COVID-19 in-country vaccine distribution network. For this network, the tactical decisions category comprises the allocation decision: the amount of vaccines to be shipped from main entry points to health facilities in a hierarchical way .

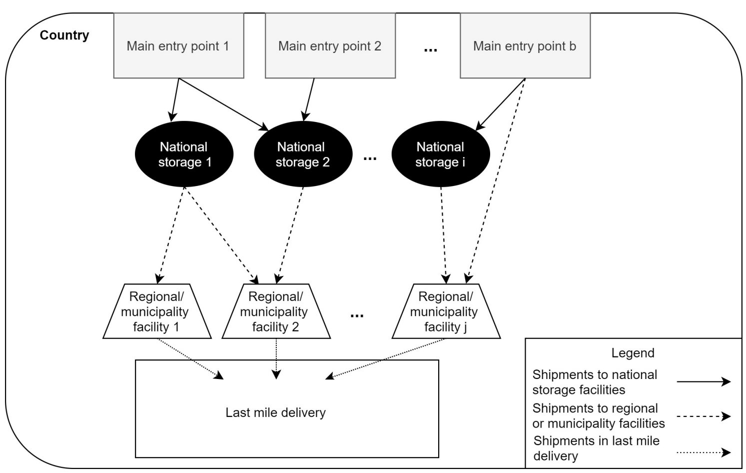

Fig. 2. Illustration of in-country vaccine distribution without local manufacturers

Compared to strategic counterparts, the tactical decisions are of high importance in the in-country vaccine distribution network in pandemics. This is due to the allocation challenge given the urgency of delivering vaccines to several health facilities and vulnerable groups, uncertainties in costs, perishability of vaccines, wastage in storage, limited capacity in facilities, and demand priorities in remote areas [24].

Moreover, infrastructure disruptions, the propagation of disease, efficacy of vaccines, and immunity duration result in huge uncertainty in both demands and supply. Furthermore, factors such as the production time of vaccines can add to the complexity of designing in-country vaccine supply chains. Furthermore, the design of in-country vaccine supply chains has multiple stakeholders such as pharmacies, hospitals, international organisations, government, manufacturers, people to be vaccinated, and many more who may have different preferences and constraints during the pandemic response [13].

2.2 Decision support for vaccine distribution

To support pandemic responders, operations management researchers have proposed different mathematical models for designing vaccine distribution networks. De Boeck et al. [10]'s recent survey shows that literature has mainly concentrated on the strategic and operational decision levels while research on decisions at the tactical level (i.e., allocation in the in-country network) is scant. That said, in this section, we consider models that address the general vaccine distribution problem.

Formulated objectives comprise an important feature of mathematical models for supporting vaccine distribution. Lemmens et al. [18] conduct a systematic literature review on the design of vaccine supply chains and contend that while the efficiency and effectiveness criteria are important, the design of such supply chains should account for sustainability, too. Moreover, a recent study confirms that including the equity objective, in vaccine distribution models is of stakeholders' interest [21]. Abila et al. [2] explore the previous successful public health strategies to test whether they could influence the uptake of COVID-19 vaccines and stress the need for equitable access to vaccines worldwide.

However, research on equitable vaccine distribution is rather new and scarce in the literature. Enayati and Özaltın [14] propose a mathematical model for equitable influenza vaccine distribution. They divided the population into several subgroups and prevented the epidemic outbreaks by equitably allocating the necessary vaccines to each subgroup. Rastegar et al. [23] develop a mathematical model for equitable influenza vaccine distribution by considering the possibility of storage for future periods, being faced with a shortage, and budget constraints. More recently, Tavana et al. [25] present a mathematical model for equitable COVID-19 vaccine distribution in developing countries. In their study, vaccines are grouped into cold, very cold, and ultra-cold categories where specific refrigeration is required for their storage and distribution. The possibility of storage for future periods, facing a shortage, budgetary considerations, manufacturer selection, order allocation, time-dependent capacities, and grouping of the heterogeneous population are among the assumptions in their study [25].

There are few available research on the COVID-19 vaccine distribution. Chen et al. [8] explore the optimal COVID-19 vaccine allocation by applying an age-structured simulation model. The results reveal that when DMs aim to minimise deaths, the optimal approach is to prefer the old age group people over the younger groups. Their research advises that when the goal is to reduce total confirmed cases, the optimal strategy could be to consider the younger group first in the vaccine allocation practice. Abbasi et al. [1] develop a DSS for optimising the COVID-19 vaccine supply chain. They formulated a conceptual model that considers a centralised booking system, risk profiling and prioritisation, and a vaccine distribution system to propose an optimised vaccine allocation model.

2.3 Research gaps

Most of reviewed mathematical models only work for single period allocations and they use static parameters (i.e., potential changes in parameters in a given timeframe are not considered). Moreover, in-line with Lemmens et al. [18] findings, very few studies have considered uncertainties (for instance, through scenario analysis [22]) when developing models to address the vaccine distribution challenges.

Besides, majority of mathematical models do not account for balancing multiple objective when investigating allocation alternatives. To the best of our knowledge, available models have been rarely developed in close collaboration with public health authorities. Lemmens et al. [18] suggest that the preferences of different stakeholders have to be taken into account for obtaining a set of economical, technological, and value key performance indicators that need to be satisfied by the design. Mills and Salisbury [21] contend that without close collaboration with practitioners models often lack relevance to and applicability for practice. In summary, there is a need for COVI-19 vaccine allocation models that realise the features of the in-country COVID-19 vaccine allocation problem while accounting for stakeholders' concerns and priorities.

3 Evidence-based mathematical model for COVID-19 vaccine allocation

3.1 Problem description

We describe the in-country COVID-19 vaccine distribution network as follows based on our discussions with public health authorities in our interviews. The vaccine distribution networks within countries often start from the main entry points of the country (e.g., international airport(s)), in which COVID-19 vaccine supplies would arrive in multiple supply waves. The first important decision is to locate storage facilities to store entered vaccines. The next critical decision is to allocate vaccines and transportation means to different facilities to distribute the vaccine in the network further. In different time steps, a distinct amount of vaccines would be allocated to localised (municipalities or districts) facilities of the country before final distribution (i.e., last mile delivery cf. Figure 2).

The distribution of a scarce amount of different types of COVID-19 vaccines to each municipality for an effective immunisation program relies on the central vaccine allocation problem (CVAP). The DMs must simultaneously consider a variety of constraints in making the allocation decision, such as the type of the vaccine, the size and distribution of the priority groups in the country, and the current infection status. Moreover, multiple objectives must be considered in the CVAP such as total coverage achieved at the national level and equity achieved across the municipalities. The cost of logistics can also be a concern, although less crucial, due to implications of decisions on saving human lives.

To simplify the problem and further investigation through mathematical modelling, assumptions are inevitable. We made the following assumptions in our methodology (derived from our discussion with authorities):

- The number and location of main entry points (MEPs), national storage facilities (NSFs), and regional/municipality facilities (RMFs) are known.
- The demands for vaccines are assumed to be measured by doses for each individual at targeted municipalities. The number of individuals and priority groups are known. Vaccines, however, are allocated in batches,
- Required times for handling the vaccines (sorting and packaging) are assumed to be negligible for the problem.
- It is assumed that the time horizon of the operation can be divided into multiple time steps. In each time step, once the allocation decision is made, the vaccines will be immediately shipped to target facilities (i.e., time divergence between deliveries at different facilities can be neglected at this stage).
- The CVAP does not consider the transportation of the vaccines within-country since the 3PL company, which has enough logistics capacity, will be responsible for the transportation.
- Since the local distribution of vaccines within each municipality differs, the question regarding how the vaccines will be delivered in the last mile is considered to be out of the scope of the problem.

3.2 Model description

Based on the insights from the background study (cf. Section 2) and interviews with public health authorities [4], we identified multiple criteria for allocating vaccines to each priority group in municipalities. The following three criteria have been commonly highlighted in the literature and expressed by stakeholders during the interview (as critical objectives).

- Efficacy is the performance dimension that shows the effectiveness of vaccine allocation [26, 7, 9, 17, 3, 6, 16, 15, 1, 8] . Demand coverage achieved among municipalities and priority groups are the main efficacy measures we consider in this project.

- Efficiency and sustainability are the dimensions related to the cost and environmental friendliness of delivering a vaccine [18]. In this study, we consider the cost of delivering the vaccine to each municipality, respectively. Logistics costs between national storage and municipalities are used to calculate the total cost of the model.
- Equity is the dimension that shows the vaccine allocation's fairness degree [21, 14, 23, 25]. For instance, distance to "perfect equity" is one of the performance metrics for measuring equity, where perfect equity is defined in terms of the priority-weighted proportional allocation amount.

To represent the problem in a mathematical form for further exploration, we propose developing a mixed-integer linear model. The main features of the model are explained as follows.

- Multiple vaccine types: vaccines may differ in terms of their batch sizes, the number of doses required per person, amount of supply, cost of transportation.
- Multiple priority groups: in each demand location, there can be several groups of the population to be vaccinated. The priority weights for each priority group can be assigned. The DM can assign different weights to different priority groups and analyse solutions before making a final decision.
- Minimum coverage level: the DM can also set a minimum coverage threshold for each priority group at each municipality. We apply a large infeasibility penalty if it is not possible to achieve the minimum coverage levels.
- Sequential vaccination between multiple priority groups: the DM can choose vaccinating different priority groups simultaneously or sequentially (i.e., after completing a given percentage of a group with higher priority).
- Objective weights: the DM can give different weights for cost and equity objectives, and obtain multiple solutions. From the model output, a Pareto front is generated that presents the value of different solutions for different objectives.
- Implementation of minimum coverage threshold for priority groups in municipalities.

Our model determines the optimum amount of vaccines to be allocated to regional and municipality facilities such that the total uncovered demands, logistics costs, transportation footprint, and the distance to perfect equity are minimised. The objectives of the model have conflicting natures; improving the coverage of demands and equity would primarily increase the logistics costs and footprint, which is not desired. For the sake of brevity, we only describe the proxies in informal terms in this section.

First objective – effectiveness: This objective minimises the total uncovered vaccines demand, as formulated below. It consists of the summation of differences between the sent vaccines to RMFs and their relevant quantity of demands in different priority groups. Our model considers that multiple vaccines have to be sent to RMFs while the minimum amount of demand coverage has to be decided by the DM(s).

$$\begin{aligned}Minimise\, uncovered\, vaccines\, demand =& Total\, vaccines\, demand\\ &- Total\, allocated\, and\, shipped\, vaccines\end{aligned}$$

Second objective – efficiency: The minimisation of allocation costs consists of ground transportation cost, air transportation cost, and penalty cost, as formulated below. The ground and air transportation costs include the transit costs from MEPs to NSFs, and from NSFs to RMFs through ground and air fleets. To account for the impact of vaccine wastage, the model considers an extra cost for each vaccine that is not allocated and transported to facilities in the network.

$$\begin{aligned}Minimise\, allocation\, cost =& Ground\, transportation\, cost\, +\, Air\, transportation\, cost\\ &+\, Penalty\, cost\, for\, extra/shortcoming\, allocation\end{aligned}$$

Third objective – sustainability: The minimisation of transportation footprint consists of considering footprint for transportation means given the travel distance, the mode of transportation (ground vs. air), and the vaccine storage requirement (cold chain equipment has fewer environmental impact than ultra cold chain equipment).

$$\begin{aligned}Minimise\, transportation\, footprint =& Ground\, transportation\, footprint\\ &+\, Air\, transportation\, footprint\\ &+\, Wastage\, footprint\end{aligned}$$

Fourth objective – equity: The minimisation of allocation discrepancies is defined as the distance to perfect proportion allocation amount. That is, given the scarce supplies and the needs of municipalities, we find the amount that corresponds to proportional allocation (what would each municipality get if supplies are proportionally allocated) and tries to reduce the discrepancy between the amount sent and the proportional allocation.

$$\begin{aligned}Minimise\, allocation\, discrepancies =& \sum(total\, shipped\, vaccines\\ &-\, the\, proportional\, allocation)\, for\, all\, regions\end{aligned}$$

4 Illustrative example

This section,illustrates our approach for generating alternatives to support the COVID-19 vaccine allocation using two examples. In the first example, as shown in Figure 3, we consider two municipalities and two priority groups in each municipality, where priority group 1 is prioritised over priority group 2. We assume that the vaccine supply is 300 units.

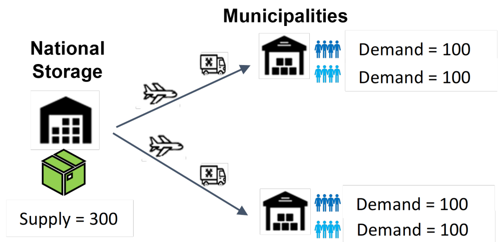

Fig. 3. Example case illustration

Demands, priority coefficients, and the equity measures are as provided in Table 1.

Table 1. Demand and priority coefficients for the example case I

Municipality	Priority group	Priority coefficient	Demand	Equity threshold
M1	P1	0.30	100	90
M1	P2	0.20	100	60
M2	P1	0.30	100	90
M2	P2	0.20	100	60

By running the optimisation model, we calculated allocated vaccine amounts, the coverage of each group in each municipality, and the difference between the number of allocated vaccines and perfect equity levels were as presented in Table 2. As the table depicts, the average percentage coverage would be 75% overall, and 85% for P1 and 65% for P2.

Table 2. Sent vaccine amounts, coverages, and deviation from the equity threshold for the example case

Municipality	Priority group	Allocated vaccine	Coverage%	Deviation from the equity %
M1	P1	100	100	10
M1	P2	80	80	20
M2	P1	70	70	-20
M2	P2	50	50	-10

In the second example, we considered a network with four municipalities (M1-M4) that have vaccine demands of 60, 30, 40, and 70 units, respectively. M1-2 are closer to the main entry point than M3-4. We also assumed the vaccine supply as 100 units. This example represents a more realistic setting as (i) the available quantity of supply is much smaller than the demand for vaccines (ii) different municipalities often have different travel time to the main entry point.

Our analysis for the second example reveals that tradeoffs between equity and efficiency objectives are huge. Figure 4 illustrates coverage graph when more importance weight has been assigned to logistics costs. Since sending vaccines to M1 and M2 is respectively less costly, the model allocates as much vaccine as possible to these two municipalities consecutively, considering the minimum threshold constraint.

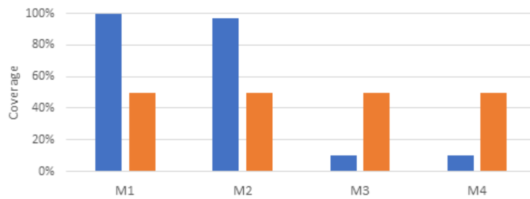

Fig. 4. Changes in demand coverage by assigning higher importance weight to logistics costs (blue: current coverage; orange: distance to equity threshold)

However, when more importance weight is given to the equity criterion, the allocation results change considerably, as shown in Figure 5.

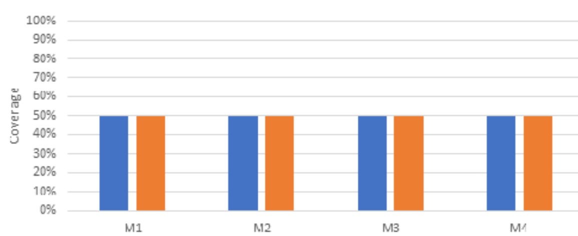

Fig. 5. Changes in demand coverage by assigning higher importance weight to equity (blue: current coverage; orange: distance to equity threshold)

To illustrate tradeoffs further, we provide a Pareto frontier diagram for logistics costs vs. the average absolute value of percentage deviation from the perfect equity level among municipalities (see Figure 6). Blue dots on this diagram refer to each alternative allocation policy.

5 Conclusions and perspectives

Over the course of year 2020, public health authorities in many countries faced a task of unprecedented scale: to ensure effective and efficient vaccine delivery to frontline healthcare workers, at-risk groups, and eventually all people while accounting for sustainability and equity. In this article, we argue that equitable allocation of scarce COVID-19 vaccines is still a challenging task.

Our primary analysis revealed that planning for an over-average equitable vaccine allocation could mean accepting nearly 40% more logistics costs. While

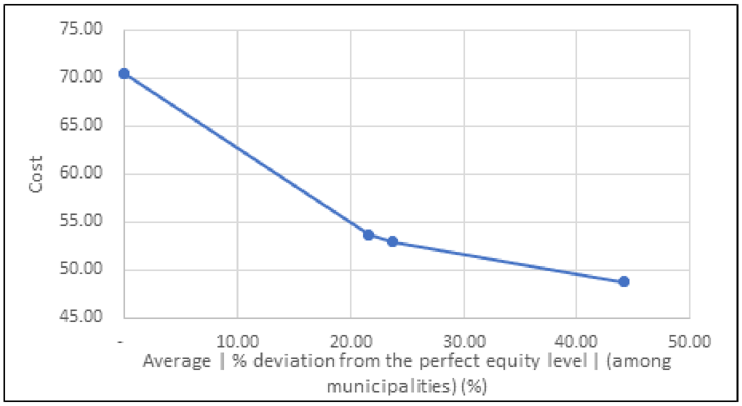

Fig. 6. Tradeoffs between efficiency and equity objectives

in high-income countries, accepting high logistics costs may not be an issue to public health authorities, this would be challenging in LMICs. Despite the significance of the challenge, the literature lacks effective decision support systems to help public health authorities. Particularly, in the presence of multiple objectives, illustrating tradeoffs between conflicting criteria is a need that has often been neglected in the literature.Previous studies in vaccine allocation and distribution [26, 7, 9, 17, 3, 6, 16, 15, 1, 8] ignore the sustainable aspect of the pandemic vaccine supply chain. Only one study by Huang et al. [16] considers the types of the vaccine in vaccine allocation decision. Based on this, we have presented the first characteristics of a decisions support system able to serve as a basis to support public health authorities for current and future pandemics. The main assumptions of this research have been derived and validated in close collaboration with authorities involved in the COVID-19 response.

To sum up, this works is still in its infancy, and there can be numerous avenues for research. First, the proposed model should be tested and validated with several real cases. Differences between contexts could imply that a generalised approach to the allocation problem across multiple countries/contexts would be difficult. One solution is to allow enough flexibility for model features (constraints, variables and parameters) so that they could to be adapted. Second, we acknowledge that since there are different infrastructure capabilities in distinct countries, the cost picture can differ from country to country and supply chains for delivering various COVID-19 vaccines within regions may differ hugely. Moreover, vaccines delivery to main entry points would naturally trigger an increase in the demand for transportation means with specific coldchain requirements. One expected result is the raised transportation costs, which will also add to the logistics costs formulated in our model. Third, other metrics for equity have to be investigated. Other metrics which could be considered to assess equity are the percentage of residents age 55 and older; the percentage of minority residents; the percentage of residents who live below the poverty line; the region's prevalence of diabetes and hypertension; the region's two-week COVID-19 infection rate; and the percentage of residents who are unvaccinated.

Fourth, this was only the first step for our DSS development. Following the process outlined in Figure 1 we need to run a sensitivity analysis on the decision alternatives that have been generated by our model. Given the uncertainties in the context of COVID-19 pandemic response, some information might be missing such as the number of available vaccines. Thus, DMs could be interested to check the sensitivity of decision alternatives (second component) based on different scenarios. Such analysis will be conducted through a pool of scenarios developed by reviewing literature and using the help of experts. Thereafter, alternatives can be ordered based on the performance in the sensitivity analysis step. Such information can provide a basis to present the outcomes in a meaningful way to DMs through an online dashboard. We intend to verify the model with public health authorities and collect their information needs to develop an intuitive web-based platform. We intend to offer a set of DMs from different high-, middle-, and low-income countries to test and validate the platform in the final stages of our research project.

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