COVID-19 Network Technology-based Responsive Action (CONTRA)

Project report #3:

Vaccine supply chain decision support system

January 2022

The CONTRA project is funded by the Research Council of Norway, grant agreement No. 321773

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Preface

The project "COVID-19 Network Technology-based Responsive Action" (CONTRA) started in June 2020. The CONTRA project initially aimed to develop a decision support system to support public health responders to distribute the COVID-19 vaccine effectively, efficiently, sustainably, and fairly. However, over the course of the project, also shown in this report, we found two important factors. First, the central allocation problem is the core of vaccine distribution inside countries: allocating different vaccines from national storage point to municipalities and regions. Second, optimizing the central vaccine allocation only based on the equity criterion could have two advantages. (a) It helps to avoid unnecessary trade-offs between several objectives that could prolong the decision-making process. (b) Based on observations that show the same behavior of effectiveness and equity measures for the central allocation problem, focusing on either of them would guarantee the other. This report summarizes the actions and results in the project, as of work package (WP) WP 3 in the period June - December 2021. In WP3, we design the decision support dashboard based on the mathematical model that we developed in WP2. We are grateful to the professionals at public health authorities and partnered businesses who have contributed with their time and expertise, and look forward to further collaboration. The project is funded by the Research Council of Norway (agreement No. 312773).

Leuven, January 2022

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Abstract

The project "COVID-19 Network Technology-based Responsive Action" (CONTRA) is funded by the Collaborative and Knowledge-building Projects for the Fight Against Coronavirus Disease (COVID-19) program[1] of the Research Council of Norway for the period June 2020 – December 2021 (extended to March 2022). The goal of the project is to contribute to the effectiveness, efficiency, equity, and sustainability of the COVID-19 response, through the development of a generic decision support system (DSS) that pandemic responders can use to help them optimize vaccine roll-out. The DSS is informed by stakeholder-centered understanding of the vaccine roll-out system, and developed using mathematical modelling and scenario analysis.

The report describes the results of the third work package (WP) in the CONTRA project. The WP3 aims to develop the decision support system by connecting the mathematical model into an intuitive dashboard that should support vaccine allocation decision. Moreover, the report presents the current status of the dashboard and the summary of our meeting with the advisory board members. Based on the current progress and the feedback from advisory board members, the next step in the project will be to complete, test and validate dashboard (components, usability, accessibility, etc.) and finalize DSS documentation. For dissemination of findings, two journal papers have been submitted recently and two other journal papers will be submitted by the end of the project.

[1] https://www.forskningsradet.no/en/call-for-proposals/2020/covid-19-emergency-call-proposals-collaborative-and-knowledge-building-projects-for-the-fight-against-coronavirus-disease-covid-19/

1. Introduction

1.1 Aim and scope of report

This is our third Progress Report. In Progress Report #1 we gave a more detailed description of aims and project partners, and describe the results from work package (WP) 1, which can be summarized as follows:

- An overview of related research on vaccine distribution networks, related decision support systems, and the progress in the literature about the COVID-19 pandemic.
- Description of the key actors in the vaccine distribution network in Norway, a map of their relation to each other in terms of control actions and information feedback loops (ACTOR MAP)
- System map of key stocks, flows of vaccines and people and the influence of information in the vaccine roll-out system, encompassing national and local levels
- Decision (based on above results) to focus DSS on the central vaccine allocation problem (CVAP) faced by Institute of Public Health (FHI) when deciding how to share out vaccine to municipalities.

In Progress Report #2, we elaborated on issues pertinent to developing a DSS tool for the CVAP, and based on this, we proposed an integer programming model to solve the CVAP. We described how features need to be incorporated into the model depending on particular decision-making needs, and how trade-offs among different objectives are expected to result in various allocation decisions.

The third report describes the latest outcomes of the WP3 in the CONTRA project. The WP3 aims to develop the decision support system by connecting the mathematical model into an intuitive dashboard that should support vaccine allocation decision. Moreover, the report presents the current status of the dashboard and the summary of our meeting with the advisory board members. Based on the current progress and the feedback from advisory board members, this report introduces the next steps that the CONTRA project researchers will try to cover till the end of the project.

1.2 Methods and dissemination

As a part of WP3, the project team arranged the 1st Hands-on workshop on March 18th, 2021, and presented the mathematical model to the concerned person at FHI. The project team members from KU Leuven, Belgium, also held a meeting with vaccine allocation authorities in Flanders. The project team also brainstormed to improve the dashboard in terms of usage and critical indicators. From the users' perspective, it was decided to include the following features: easy-to-interpret graphs, compare scenarios visually, outcomes visualized over time, and visualize uncertainty. It was also decided to include the following key indicators: vaccination allocated per municipality, deviation from target, deviation from planning, the ecological footprint of vaccination strategy, and waste of vaccine.

Under WP III, the project team organized the 2nd Hands-on workshop on May 27th, 2021. During the workshop, the project team completed the sketch design and agreed on the programming framework for the vaccine supply chain decision support system. The project team also attended European Public Health Conference workshop about COVID-19 dashboards. As a part of dissemination and publication activities for the WPIII, the project team has organized a special issue at the Journal of Humanitarian Logistics and Supply Chain Management. The project team also presented one conference paper at NOKOBIT 21. Finally, the team is also working on one Journal paper that covers the conceptual systems map.

1.3 Structure of the report

Section 2 provides a brief review of outcomes of WP2 plus additional updates that we made to the model in the course of the WP3. The decision support system is presented in Section 3. Section 4 includes a brief overview of the dashboard and the ongoing development process. Section 5 summarizes the comments and suggestions from the advisory board members. We conclude the report and point to further steps in the project in Section 6.

2. Update in the problem description and mathematical model

Based on our findings from the stakeholder meetings and system mapping in WP1, we characterize the decision-making environment of the vaccine allocation system at national level and develop a mathematical model to support the vaccine allocation decisions. In this section,

we describe the updated problem (Section 2.1), present our mathematical modeling approach (Section 2.2), and present results (Section 2.3).

2.1 Problem Description and Assumptions

The vaccine distribution network within a country starts from the main entry point of the country, in which COVID-19 vaccine supplies can arrive in multiple supply waves. In each supply wave, the vaccines, which arrive at a national storage point must be allocated among the smaller administrative units (municipalities or districts) of the country. The decision makers must consider a variety of factors simultaneously in making allocation decisions such as the type of the vaccine, the size and distribution of the priority groups in the country, and the current status of infection.

In Norway, the Norwegian Institute of Public Health (FHI) is responsible for determining the number of different vaccine types to allocate to each municipality. In Norway, there are 356 municipalities and a single national storage point. Each municipality differs in size, population, dispersion of each priority group, and distance to the national storage point. The vaccine supply amount is certain. However, there are scarce number of vaccines compared to the size of the population in each municipality. Therefore, prioritization among different population groups exists (such as health care personnel, chronic patients, elderly and vulnerable groups, employees in priority sectors, etc.). The FHI decides on which of the priority groups will be vaccinated in each supply wave. There are multiple vaccine types, which have various characteristics and requirements (such as available supply amount, number of doses required, batch size, unit (per batch) cost of delivery, cold storage requirements, etc.).

Considering the current vulnerability of the population to coronavirus disease and priority groups in each municipality, we frame a decision making problem, which addresses the distribution of the scarce amount of different types of COVID-19 vaccines to ship to each municipality and allocation of vaccines among priority groups within each municipality. We focus on one-time allocation of a given amount of supplies among regions. Without loss of generality, we consider allocation of limited supply of vaccines from a national storage point

among municipalities that involve multiple eligible priority groups. We call this problem as the central vaccine allocation problem (CVAP).

Figure 1 shows an example small network representation for the CVAP. In the national storage, there are supply batches of two vaccine types. Since in the real-world problem, vaccines are distributed in batches, we also consider allocating vaccine batches. There are four municipalities (M) with two different priority groups. The CVAP aims to determine the allocation of vaccine batches to each priority group of each municipality. The allocation unit is the number of individuals vaccinated by the required doses.

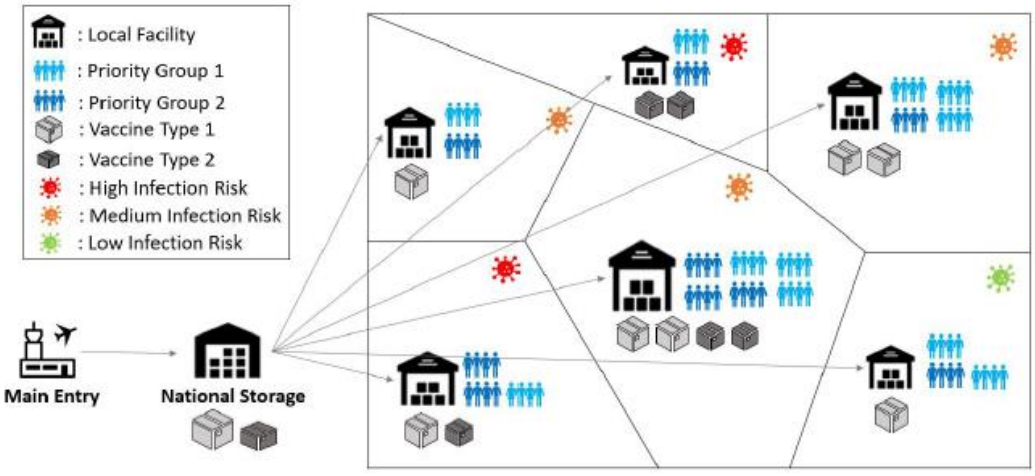

Figure 1. An example vaccine distribution network for CVAP

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. Besides, the local distribution of vaccines within each municipality differs. Therefore, we keep decisions regarding how the vaccines will be delivered in the last mile within each municipality out of the scope of the problem.

Specifically, we define effectiveness in terms of the average coverage level (i.e., the ratio of amount received to the total needs) achieved in the network by considering priority importance of municipalities and priority groups for vaccination. Equity is defined based on the differences

among regions in terms of the amount of deviation from pre-determined fair coverage levels, which are computed based on a weighted pro-rata allocation policy. The cost (efficiency) of the vaccine allocation decision is not considered as a primary concern in CVAP. However, if needed, the cost of the vaccine allocation plan can be included in the model by considering the unit cost of shipping vaccines to municipalities.

2.2 Mathematical Model

We propose an integer programming model to solve the CVAP. The mathematical model can incorporate different features depending on the decision making needs; that is, the features can be selected by the decision maker in the final implementation. Our general framework is presented in Figure 2.

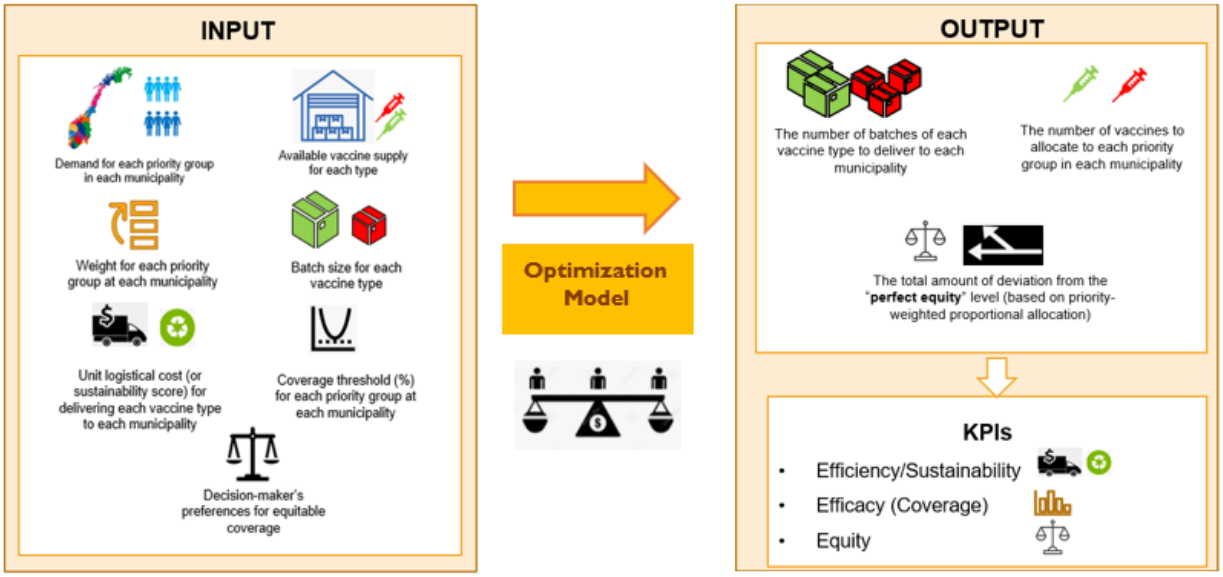

Figure 2. Input, Output and KPIs of the CVAP

The main features of the model are summarized below:

- Vaccine types. We focus on allocating available supplies for multiple types of vaccines. We assume that vaccines may differ in batch sizes (i.e., the number of vaccines in a cargo package), resulting from different cold chains or logistical requirements, and consider a

batch of vaccines as the smallest unit for allocation. Since a batch cannot be divided, the amount allocated to municipalities can be an integer multiple of batch size.

We also assume that the required doses for complete vaccination may be different for different vaccines. In CVAP, available supply for each vaccine type is defined based on the necessary number of doses for fully immunizing one person. Therefore, CVAP solutions (i.e., the allocated amount of vaccines allocated) are also defined based on the number of individuals that can be fully vaccinated.

- Capacity. The capacities of municipalities to store and administer vaccines over the planning horizon may be limited due to various infrastructural challenges and resource availability. We assume that the total number of vaccines to be sent to each municipality is limited based on the total number of vaccines of each type that can be stored and administered in the municipality during the planning horizon.

  We note that our model does not explicitly consider detailed transportation planning of COVID-19 vaccines; that is, we assume that the proposed allocation amounts can be transported to the municipalities. For instance, a third-party logistics (3PL) company is responsible for the transportation of the COVID-19 vaccines in Norway, and logistic capacity is not a limitation according to the existing contracts. However, if there exist logistical limitations or preferences of decision makers to send certain vaccine types to different municipalities, capacity parameters can be used to control the amount of vaccines to ship to different regions.

- Multiple priority groups: In each demand location, there can be several groups of population to be vaccinated. The priority weights for each priority group can be assigned. The decision-maker can assign different weights to different priority groups and analyse solutions before making a final decision.

- Minimum coverage level: The decision-maker 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.

- Allocation policy. Given a number of eligible priority groups dispersed across a given country, public health authorities can consider different allocation policies in rationing supplies. For example, available supply of vaccines can be divided by simply applying pro-rata (proportional) allocation policies to aim for the same coverage level for different priority groups in all regions. However, ignoring regional differences in infection risks and social vulnerability and targeting the same level of vaccination coverage across different groups and regions may not be desirable in terms of effectiveness and equity. Moreover, due to capacity limitations, achieving the same coverage levels across priority groups and regions may not even be feasible. Additionally, public health authorities may want to control the amount of vaccine to allocate to different priority groups; for instance, allocating more vaccines to higher priory groups may be desirable. Our model aims to achieve an equitable allocation by prioritizing risky and vulnerable regions as well as considering capacity limitations and the bounds set by the decision maker.

In the proposed allocation policy, we skew vaccine rations in favor of higher priority groups and risky areas by assigning importance weights. Public health authorities can specify the relevant dimensions that affect risk and vulnerability by using their expert judgment or available data. Specially, given a dimension l, the normalized importance weight for municipality m is denoted by λ_m^l. The hierarchical criticality weights assigned to each priority groups τp and municipality λ_m^l. are then merged to obtain a composite weight score αmp by computing geometric average as shown in Figure 3, which plays an important role to determine perfect equity levels and allocation amounts in our model.

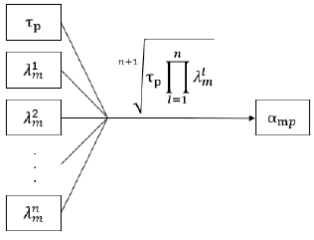

Figure 3. Input, Output and KPIs of the CVAP

In the model, perfect equity is the key element to ensure the equity dimension of the multi-objective resource allocation problem among municipalities and priority groups. A perfect equity amount, which is a weighted proportional allocation amount for each priority group in each municipality, is computed. The total vaccine supply amount, demand, and priority weight of each priority group in each municipality are necessary to calculate the perfect equity levels.

The outputs of the model are the number of batches of each vaccine type to deliver to each municipality, the number of vaccines to allocate to each priority group in each municipality, and the total amount of deviation from the perfect equity level. The resulting outputs are analyzed considering multiple key performance indicators (KPI) that measure effectiveness and equity.

The notation and the optimization model developed to solve CVAP is presented below.

$\mathcal{M}$: set of regions (municipalities); $m \in \{1, ..., M\}$
$\mathcal{P}$: set of priority groups; $p \in \{1, ..., P\}$
$\mathcal{K}$: set of vaccine types; $k \in \{1, ..., K\}$

Model parameters

d_{mp}: size of targeted unvaccinated population in priority group p in municipality m
α_{mp}: composite weight of priority group p in municipality m
g_{mp}: minimum percentage of demand to cover for priority group p in municipality m (i.e., minimum coverage threshold)
f_{mp}: weighted-proportional allocation amount for priority group p in municipality m (i.e., the perfect equity level)
b_k: batch size (number of vaccine) for each vaccine type k
c_{mk}: capacity of municipality m for vaccine type k
$\bar{s}_k$: available total vaccine supply for each vaccine type k
s_k: amount of supply that will be allocated for vaccine type k; $s_k = \min\{\bar{s}_k, \sum_m c_{mk}\}$
γ: large penalty amount imposed for the infeasibility of minimum coverage threshold

Decision variables

X_{mpk}: number of vaccines to allocate to priority group p in municipality m of vaccine type k
Y_{mk}: number of vaccine batches to allocate to each municipality m of vaccine type k
W_{mp}: amount of deviation from perfect equity of municipality m for priority group p
U_{mp}: absolute value of W_{mp}
V: auxiliary variable that defines the maximum gap between achieved coverage and the minimum coverage threshold

Objective function

$$\min \quad \sum_{m=1}^{M}\sum_{p=1}^{P}\frac{\alpha_{mp}U_{mp}}{d_{mp}}+\gamma V \qquad (1)$$

The first term of the objective function (1) minimizes the weighted sum of the absolute deviation amount from the fair coverage level, which is equal to the ratio of the perfect equity level with respect to the demand size of each priority group in each municipality. The second term in (1) applies a large penalty if the minimum coverage threshold set for a priority group in a municipality cannot be met, which is defined by constraints.

Constraints

$$\sum_{p=1}^{P} X_{mpk} = b_k Y_{mk} \qquad \forall m \in \mathcal{M}, k \in \mathcal{K} \qquad (2)$$

$$\sum_{m=1}^{M} b_k Y_{mk} = s_k \qquad \forall k \in \mathcal{K} \qquad (3)$$

Constraints (2) calculate the total number of vaccines sent to each municipality based on the number of vaccines that are available in a batch for each vaccine type. Constraints (3) ensure that the total amount of vaccines set to the municipalities for each type is equal to the total amount of supply that will be allocated.

$$\sum_{k=1}^{K} X_{mpk} = f_{mp} + W_{mp} \qquad \forall m \in \mathcal{M}, p \in \mathcal{P} \qquad (4)$$

$$-U_{mp} \leq W_{mp} \leq U_{mp} \qquad \forall m \in \mathcal{M}, p \in \mathcal{P} \qquad (5)$$

Constraints (4) de_ne the amount of deviation from the perfect equity level for each priority group in each municipality, and constraints (5) compute the absolute value of the deviation from this perfect equity amount.

$$f_{mp} + W_{mp} \leq d_{mp} \qquad \forall m \in \mathcal{M}, p \in \mathcal{P} \qquad (6)$$

$$g_{mp} d_{mp} - \sum_{k=1}^{K} X_{mpk} \leq V \qquad \forall m \in \mathcal{M}, p \in \mathcal{P} \qquad (7)$$

Constraints (6) ensure that the total of perfect equity level and the deviation from the perfect equity level for each priority group in each municipality is limited with its demand level. Constraint (7) determine the maximum amount of deviation from the given minimum demand coverage thresholds.

$$b_k Y_{mk} \leq c_{mk} \qquad \forall m \in \mathcal{M}, k \in \mathcal{K} \qquad (8)$$

Constraints (8) ensure that the capacity constraints of each municipality for each vaccine type are respected. Finally, constraints (9)-(13) define the domains of variables.

$$X_{mpk} \geq 0 \text{ and integer} \qquad \forall m \in \mathcal{M}, p \in \mathcal{P}, k \in \mathcal{K} \qquad (9)$$

$$Y_{mk} \geq 0 \text{ and integer} \qquad \forall m \in \mathcal{M}, k \in \mathcal{K} \qquad (10)$$

$$W_{mp} \text{ urs and integer} \qquad \forall m \in \mathcal{M}, p \in \mathcal{P} \qquad (11)$$

$$U_{mp} \geq 0 \text{ and integer} \qquad \forall m \in \mathcal{M}, p \in \mathcal{P} \qquad (12)$$

$$V \geq 0 \text{ and integer} \qquad (13)$$

The presented CVAP model ensures effectiveness through constraint (3). If the whole supply was not enforced to be distributed, due to reasons that cause shortages from perfect equity levels in some population groups (e.g., capacity limitations, minimum threshold coverage constraints, batch sizes), there could be available vaccines that are not allocated to other population groups, since exceeding perfect equity level is also penalized in the objective. This change would lead to a less effective allocation. Also, achieving an effective coverage level for population groups is ensured with the objective since it provides a higher level of coverage for more critical population groups. While ensuring an effective allocation, the objective also provides an equitable allocation in the network by the definition of the perfect equity level. The aim of this model is to be equitable rather than equal. The perfect equity level determines the number of vaccines to allocate to priority groups in municipalities considering multiple important factors, as explained

before. Thus, minimizing the deviation from the fair coverage levels, driven by the perfect equity amounts, leads to a network-level equitable solution

Finally, in CVAP, we define the perfect equity level before solving (1)-(13) as follows:

$$f_{mp} = \begin{cases} \dfrac{\sum_{k=1}^{K} s_k d_{mp} \alpha_{mp}}{\sum_{m=1}^{M} \sum_{p=1}^{P} d_{mp} \alpha_{mp}}, & \text{if} \dfrac{\sum_{k=1}^{K} s_k d_{mp} \alpha_{mp}}{\sum_{m=1}^{M} \sum_{p=1}^{P} d_{mp} \alpha_{mp}} \leq d_{mp} \\ d_{mp}, & \text{otherwise} \end{cases} \qquad \forall m, p \qquad (14)$$

The main components used for calculating the perfect equity level are the size and the composite weight of a priority group in a municipality, and the total supply. Since the number of vaccines to be allocated to a population group in a municipality can not exceed its demand, the upper bound for perfect equity level is set as the demand of the population group in that municipality.

2.3 Numerical Results

In this section, we conduct numerical analysis to gain insights into how different parameter settings and allocation policies induce a change in the allocation decisions and key performance indicators (KPIs). We first present the set of KPIs used to evaluate the performance of the solution. We then we present our main results for a case study with real world data. In our numerical experiments, we solve the CVAP by using CPLEX with default solver parameters. Our model is coded with Java and Concert Technology and solved on a computer with Windows 10 operating system with Intel Core i7-7700HQ CPU 2.8 GHz and 16 GB of RAM.

Key performance indicators (KPIs)

We propose several KPIs for decision makers to evaluate the equity and effectiveness of each allocation solution. The list and descriptions of the KPIs are provided in Table 1. Decision makers can consider one or more metrics to assess the quality of allocation solutions.

Table 1: KPIs for evaluating equity and effectiveness of CVAP solutions

	KPI Type	KPI No.	KPI Description	KPI Notation
Municipality (Aggregate) level	Equity	KPI 1a	Standard deviation of total coverage (among municipalities)	StDev $[\hat{Z}_m]$
	Equity	KPI 2a	Range of total coverage (among municipalities)	Range $[\hat{Z}_m]$
	Equity	KPI 3a	Minimum total coverage (among municipalities)	Min $[\hat{Z}_m]$
	Equity	KPI 4a	Gini coefficient for the total coverage (among municipalities)	Gini $[\hat{Z}_m]$
	Equity	KPI 5a	Average of the absolute value of difference between total fair coverage and total achieved coverage (among municipalities)	Avg $[\lvert\hat{\Delta}_m\rvert]$
	Equity	KPI 6a	Maximum difference between total fair coverage and total achieved coverage (among municipalities)	Min $[\hat{\Delta}_m-]$
	Effectiveness	KPI 7a	Average total coverage (among municipalities)	Avg $[\hat{Z}_m]$
	Effectiveness	KPI 8a	Weighted total coverage (among municipalities)	WAvg $[\hat{Z}_m]$
Priority group level	Equity	KPI 1b	Standard deviation of coverage for each priority group (among municipalities)	StDevP $[Z_{mp}]$
	Equity	KPI 2b	Range of coverage for each priority group (among municipalities)	RangeP $[Z_{mp}]$
	Equity	KPI 3b	Minimum coverage for each priority group (among municipalities)	MinP $[Z_{mp}]$
	Equity	KPI 4b	Gini coefficient for the coverage for each priority group (among municipalities)	GiniP $[Z_{mp}]$
	Equity	KPI 5b	Average of the absolute value of difference between fair coverage and achieved coverage for each priority group (among municipalities)	AvgP $[\lvert\Delta_{mp}\rvert]$
	Equity	KPI 6b	Maximum difference between fair coverage and achieved coverage for each priority group (among municipalities)	MinP $[\Delta_{mp}-]$
	Effectiveness	KPI 7b	Average coverage for each priority group (among municipalities)	AvgP $[Z_{mp}]$

Case study results

We present a case study based on Turkey's vaccination data to illustrate the implementation of the proposed approach.

In Turkey, COVID-19 vaccine administration started in early January 2021, and healthcare personnel, elder people, people with chronic diseases and essential workers were among the initial priority groups. Eligible groups for vaccination have been announced through different media channels sporadically, and appointments have been made through an online digital

platform or the telephone appointment system of the Turkish Ministry of Health. Vaccines have been administered both at family health centers and hospitals, and eligible groups have been given the opportunity to choose either Sinovac or Pfizer-BionTech vaccines.

We consider within-country allocation of vaccines by focusing on the vaccination coverage levels, eligible groups and available supply on March 29th, 2021. On this date, the Pfizer-BioNTech

vaccine has started to be used for the first time in the country, in addition to Sinovac vaccines which had been administered since January 14th 2021. Moreover, the attained vaccination coverage and supply availability were still low at that period, and allocation of vaccines was a critical decision for public health authorities. Speci_cally, only 9.75% of the total population was given the first dose, and 7.15% of the total population was given both doses of Sinovac in the country Ucar et al. (2021). The coverage levels across the country are presented in Figure 5. In Online Appendix, we present the data for total and eligible population sizes and the firrst dose coverage percentages of the 81 municipalities as of March 28th, 2021. In order to obtain the eligible population in each municipality, we excluded the infected, deceased, and recovered population from the total population. Moreover, the eligible population does not include the population that have received their first dose of vaccination. We assume that the arriving vaccine supply will be allocated among municipalities by considering their demand for first doses. That is, we divide the arriving supply of both vaccine types to factor out the demand for second doses.

To implement our model, we have obtained a signi_cant portion of the necessary data from the publicly available sources. In Table 2, we provide a summary of our data sources that are utilized to generate and estimate model parameters.

Table 2: Data sources used to set input parameters of the case study

Model parameter	Data sources used to estimate model parameters
Population of different priority groups at each municipality, d_{mp}	Population of age groups from Turkish Statistical Institute (2021); Number of healthcare personnel from Basara Bora et al. (2019)
Infection risk weights, λ_m^1	Number of infected people and population in each municipality from Ucar et al. (2021) and Turkish Statistical Institute (2021), respectively.
Socio-economic vulnerability weights, λ_m^2	Human Development Index for each municipality from TEPAV (2020).
Batch sizes for Sinovac and Pfizer-BioNTech vaccines, b_k	The minimum shipment size is set based on information from Sinovac and Pfizer-BioNTech vaccines from SputnikNews (2021) and Minnesota Department of Health (2021), respectively.
Amount of vaccine supplies for Sinovac and Pfizer-BioNTech vaccines, s_k	Expected available doses in Turkey for Sinovac and Pfizer-BioNTech vaccines by the end of April 2021 from NTV (2021) and Bloomberg (2021), respectively.
Vaccination capacity for Sinovac and Pfizer-BioNTech vaccines, c_{mk}	Past daily vaccination statistics at each municipality from Ucar et al. (2021)

We evaluate the following four vaccination plans in our case study to gain more insights on CVAP solutions.

- Plan 1: Pro-rata allocation. The vaccines are distributed to municipalities proportional to their demand.
- Plan 2: On top of Plan 1, importance of priority groups in each municipality are incorporated.
- Plan 3: On top of Plan 2, the infection risk weights of municipalities are considered.
- Plan 4: On top of Plan 3, regional di_erences in socio-economic vulnerability are considered.

In Figure 4, we present the coverage levels of 81 municipalities for each allocation plan. In the figure, histograms for each plan show the number of municipalities covered at different levels.

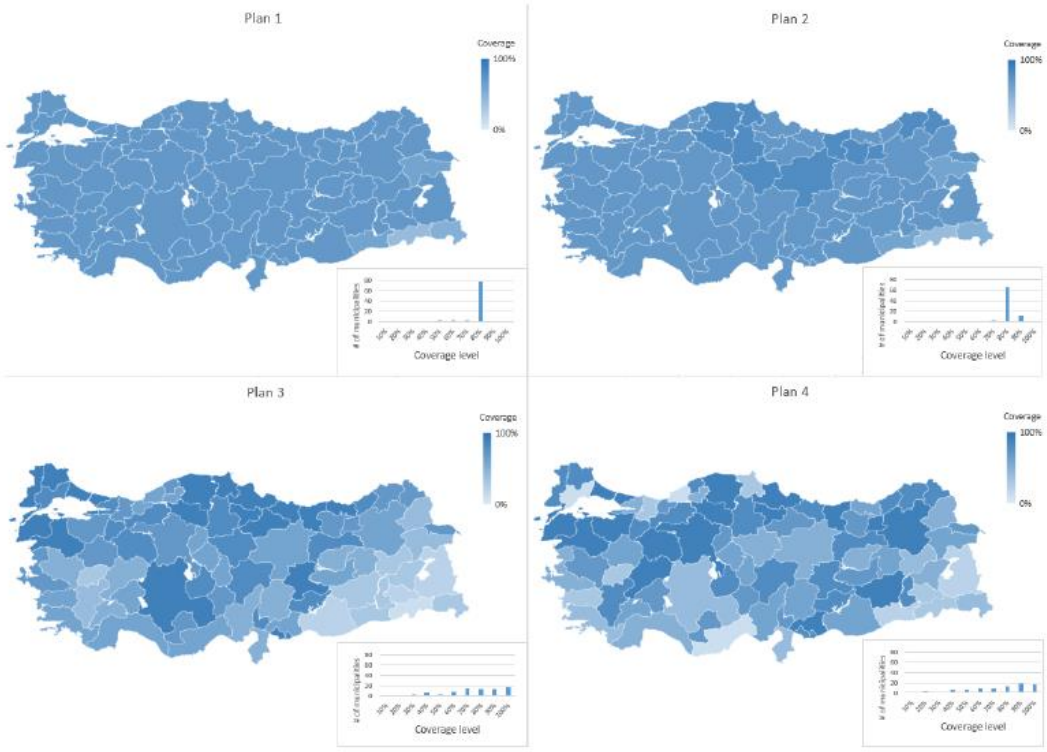

Figure 4. Coverage levels of municipalities with different plans for case study

Moreover, Figure 5 shows the fair coverage and achieved coverage levels for municipalities under different prioritization schemes.

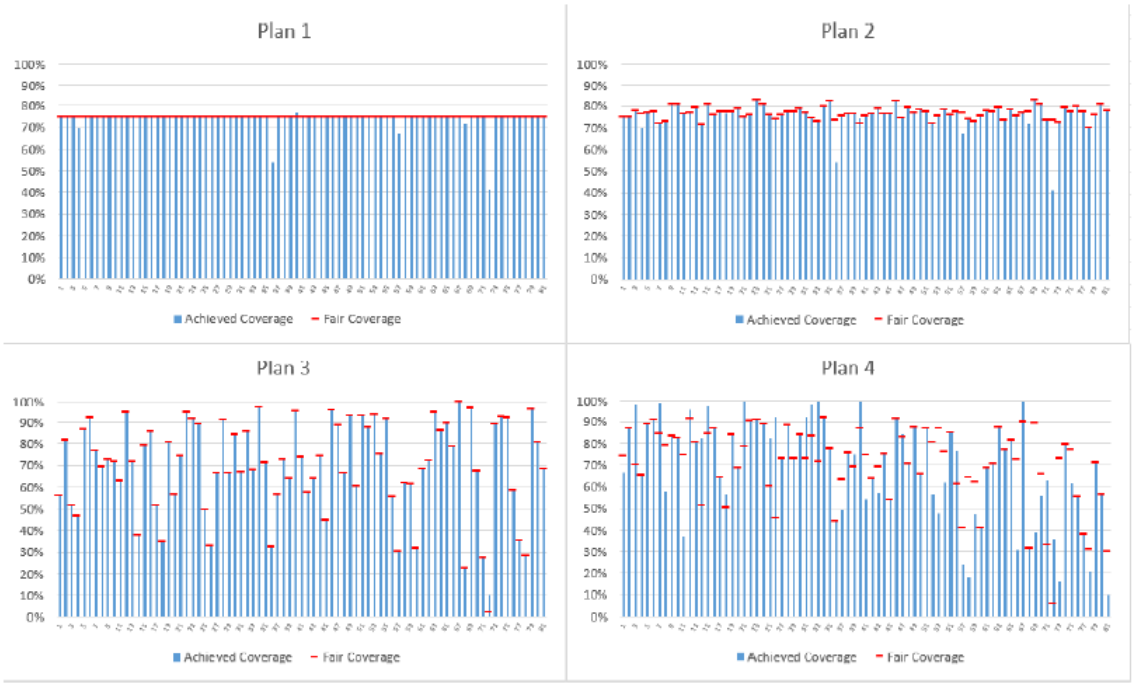

Figure 5. Achieved coverage and fair coverage levels of municipalities with different plans for case study

According to results, under Plan 1 and Plan 2 we observe nearly the same coverage levels for all the municipalities as we ignore the regional differences. However, diferent than Plan 1, under Plan 2, some municipalities receive higher number of vaccines due to the consideration of priority groups. Under Plan 3 and Plan 4, we also observe the effect of considering regional differences. According to Plan 3, municipalities with higher infection risks are prioritized; that is, the Eastern parts of the country received less number of vaccines, whereas coverage levels become higher especially in the Northern, Northeastern andWestern parts of the country. Under Plan 4, we observe that more importance is given to the internal and Eastern parts of the country due to the inclusion of vulnerability scores.

In the following, we analyze the equity and effectiveness of each plan according to our KPIs. We provide the KPIs values that evaluate equity and effectiveness of different solutions at the municipality level in Table 3. We observe that Plan 1 yields the most equitable municipality-wise coverage as can be observed from the values of equity metrics. Under Plan 2, the equity related metrics related slightly worsens compared to Plan 1. The increases in the values of StDev [Zm]

and Gini [Zm] are observed due to the consideration of population groups' relative importance. However, the related values are still significantly low, indicating municipality-wise equity is almost provided. Plan 3 and Plan 4 perform worse in terms of equity related metrics. Relatively high values of StDev [Zm], Range [Zm], and Gini [Zm] indicate that differentiating municipalities according to the infection risk and vulnerability scores causes less equitable allocation decisions.

Table 3: KPI values for the case study

KPI No.	KPI	Plan 1	Plan 2	Plan 3	Plan 4
KPI 1a	StDev $[\hat{Z}_m]$	4.48%	5.51%	21.28%	22.61%
KPI 2a	Range $[\hat{Z}_m]$	35.57%	41.49%	89.94%	89.97%
KPI 3a	Min $[\hat{Z}_m]$	41.24%	41.24%	10.06%	10.02%
KPI 4a	Gini $[\hat{Z}_m]$	0.01	0.03	0.17	0.18
KPI 5a	Avg $[\lvert\hat{\Delta}_m\rvert]$	0.92%	0.97%	0.12%	12.80%
KPI 6a	Min $[\hat{\Delta}_m-]$	-33.69%	-31.99%	-0.22%	-57.14%
KPI 7a	Avg $[\hat{Z}_m]$	74.07%	75.86%	69.89%	69.49%
KPI 8a	(λ_m^1) WAvg $[\hat{Z}_m]$	75.55%	75.24%	86.37%	83.12%
KPI 8a	(λ_m^2) WAvg $[\hat{Z}_m]$	76.33%	75.25%	68.75%	69.19%

3. Decision support tool

We developed a decision support system (DSS) for the central vaccine allocation problem in the form of a dashboard user interface. The DSS will be based on the mathematical modeling and embeds a single period allocation optimization (model will be published separately) and will guide the decision-maker to allocate the available vaccines in a fair, efficient, effective, and sustainable way. As shown in Figure 6, we divided the dashboard into different sections: input variables, decision variables, and outcomes. The input variables are given and fixed data such as the national supply of the vaccines, which are both vaccines already delivered as well as confirmed and planned deliveries, the handling capacity of the municipalities, the total number of people who need to be vaccinated and the number of people in each priority group. The decision variables are variables on which the decision-maker has an influence. They include the number of vaccines allocated to the different municipalities and to the different priority groups. Based on a particular strategy, e.g., equity, efficient distribution, or risk score (population numbers, socioeconomic disparities, epidemiological risk), the decision-maker can evaluate

these factors and can see what the result would be in the outcome section. The outcomes can be vaccination allocation to different municipalities and to the priority groups and deviations from the initial target coverage. Based on initial stakeholder feedback from the Flemish agency of Health and Care, which is responsible for vaccine allocations in Flanders, and the insights from a dashboard workshop at the 14th European Public Health (EPH) conference, the importance of visualizing the results of the mathematical optimization model on a timeline was confirmed. This way, the deviations from the plan can be anticipated. Based on these deviations, the decision-maker can subsequently go back to the section with the decision variables and adapt his previously made tradeoffs in order to optimize the outcomes. In a next stage, it will also be important to give feedback from the real-life results of the implemented decision, such as present vaccination uptake per municipality and priority group, to the input data in order to continuously enhance the accuracy of the DSS. Currently, we are building this DSS and are preparing validation and optimization based on pilot testing and feedback from stakeholders.

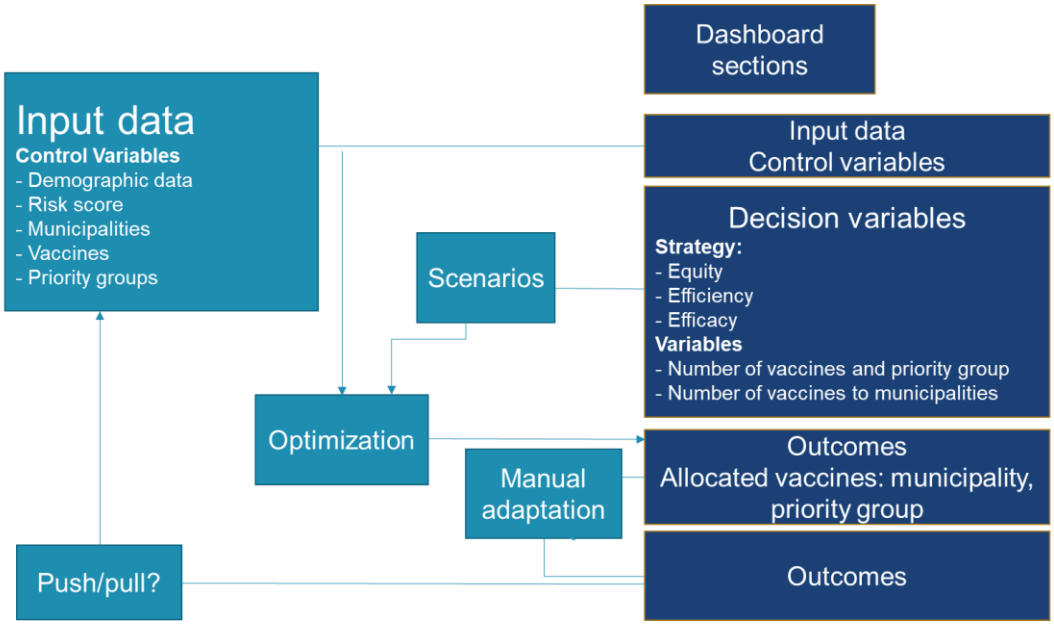

Figure 6. Dashboard parts

4. Dashboard development

We are developing the dashboard iteratively after lean principles, based on gathering new information and insight continuously. Thus, the development process has naturally taken us in a somewhat different direction than when we started sketching.

The purpose of the dashboard is, however, still the same: to make it easy for decision makers to know how much vaccine to distribute to each priority group in each municipality. The difference between the early sketches and the current iteration of our dashboard software revolves mainly around the means of data input. Currently, the dashboard looks like Figure 7.

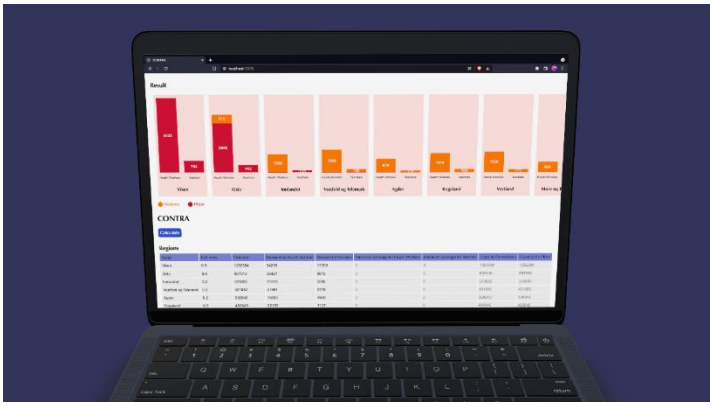

Figure 7. Presentation of the dashboard

4.1 API data vs Direct input

In the beginning, our early assumption was that most of the data would be available as APIs. Thus, the software could integrate to the APIs seamlessly. However, this kind of data access can not be taken for granted in certain countries. We want to ensure that the dashboard will work and perform regardless of country and API availability. Therefore, our next iteration of the dashboard has been designed with flexibility in mind when it comes to data input, with a higher emphasis on copying and pasting data from a spreadsheet (see Figure 8).

With the current dashboard, we aim for super easy ways of copying and pasting whole rows and columns of data - along with quick input in multiple rows or columns simultaneously. The dashboard heavily relies on well-known user patterns found in spreadsheets – ensuring that data can be put in and tinkered with quickly and efficiently. However, this does not remove the option of data import – it merely provides smooth data input even if an API import is out of the question. We are currently also working on graphical visualizations for more of the KPIs based on the scenario calculations. We are also considering different means of sharing the scenario calculations.

Regions

Name	Risk score	Demand	Demand for Health Workers ICU	Minimum coverage for Health Workers ICU	Capacity for Moderna	Capacity for Pfizer
Viken	0.5	1252384	980	0	1252384	1252384
Oslo	0.8	697010	719	0	697010	697010
Innlandet	0.3	370603	420	0	370603	370603

Add row Clear Counties of Norway

Priority groups

Name	Risk score
Health Workers ICU	0.8
Health Workers	0.2
Elderly	0.1

Add row Clear

Vaccines

Name	Supply	Batch size
Moderna	10000	1
Pfizer	10000	1

Add row Clear

Figure 8. Presentation of input data

4.2 Streamlining the user interface

The followings are a few more details around the current Dashboard workstream.

- A good user interface should be intuitive and natural. In order to be intuitive and natural, we need to build upon users expectations which comes from prior experience. "Everyone" is familiar with excel and tables and inserting data is "simple".

- A more important reason for the excel-like layout is to make this work well in any country independent of availability of data. We assume it is the decision makers who has the latest up-to-date numbers and we streamline the process for them feeding it into the model. We believe decision makers should be able to copy paste from and to excel.

- Whenever a value is changed the graphs are updated making it easy for the decision makers to see the impact.

4.3 Critical features not yet implemented

Figure 9 shows the current workload that we follow to finalize the dashboard. There are still some features that we need to work on:

- Copy paste support to and from excel

- Showing several different types of graphs (including but not limited to percentage and equity level threshold)

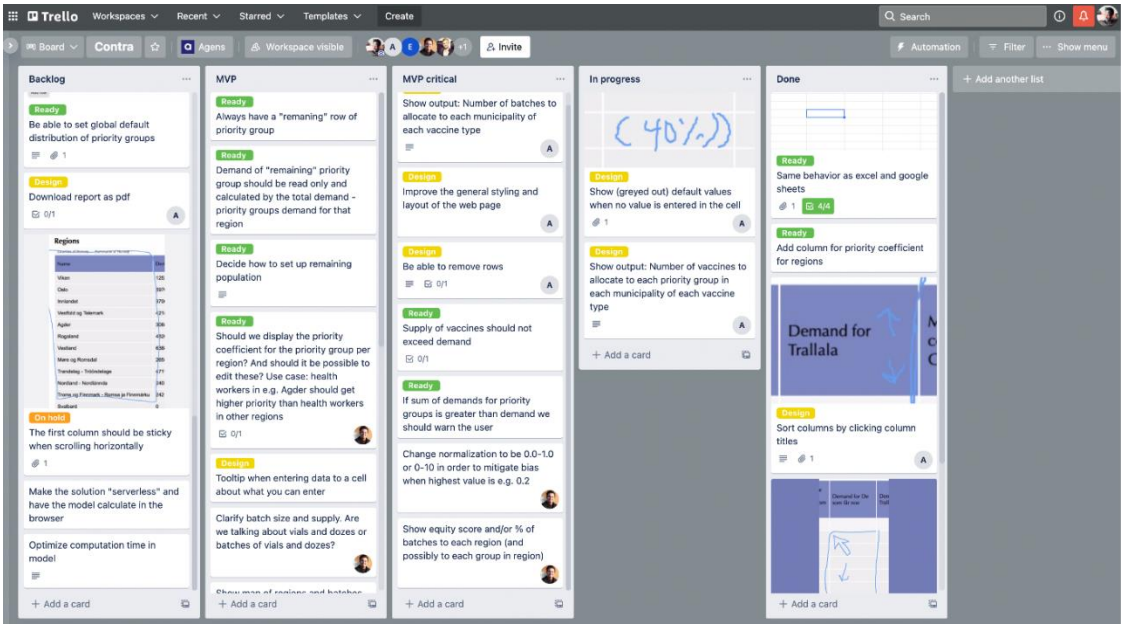

Figure 9. Workflow of dashboard development on Trello

- Easy to export reports, charts and vaccine distribution data in PDF format

- Easy to export and import data in order to collaborate on model input

- General UX improvements to "make the tool work for you and not against you"

- Visualize when demand is met/fullfilled

Desirable features not yet implemented

- Run the constraint solver in the browser to have the model be independent of cloud solutions

- Make it easy to "travel in time", save snapshots and compare earlier input data and see difference in vaccine allocation and equity levels[1]

4.4 Distribution of the software and shortcomings

With respect to this issue, the following points are important:

- We will open source the project and decision makers should be able run it either partially or entirely locally. Some software and hardware requirements may incur.

[1] A full list of tasks to be done can be seen here: https://trello.com/b/Zli2GQtA/contra

We have not been able to start working up close with decision makers – which means we need to do certain adjustments before a decision maker is able to start using it.

We guess and expect DM's to want changes in:

- Vaccines Vs. dozes Vs. vials Vs. batches

- Capacity per distribution Vs. capacity per delivery

- Long (yearly?) vaccine allocations & prioritization Vs. many (weekly?) small iterative vaccine allocations & prioritization

- Support for political, arbitrary rules

5. Notes from meeting with Advisory board members

The meeting with advisory board members was conducted on December 9th, 2021 digitally through Zoom. Members of the board are Professor Matthieu Lauras (IMT Mines Albi, France), Professor Fabio Sgarbossa (NTNU, Norway), and Professor Anne Berit Walter (UiO, Norway). In the meeting, Project Manager, Dr. Baharmand presented the project progress and findings for 50 minutes. Thereafter, there was the Q&A session with advisory board members for 1 hour.

The overall feedback from advisory board members was positive. For instance, Prof. Sgarbossa found the dashboard “nice, flexible and user friendly”. We also received detailed comments and questions about different parts of the project. Prof. Walter was wondering about how we get numbers on the dashboard updated and whether we have planned for those countries that might have difficulties to get input data for the model parameters. Prof. Sgarbossa asked how we are planning to estimate the demand for vaccines as this might not be a straightforward task in some contexts. Prof. Lauras however was more concerned about the sensitivity of model outputs with respect to small changes on input numbers.

With respect to the above mentioned comments and questions, project partners prepared a detailed plan to address the issues and provide justifications (if necessary) to model and dashboard. Reflections about these changes will be provided in the next project report. Moreover, project partners and advisory board members agreed for the second meeting on March 2022.

6. Conclusions and next step

This report highlights the CONTRA project's progress over the course of work package (WP) 3. In this WP, the decision support system (DSS) is further extended and developed based on the mathematical model and simulation described in WP 2. The DSS is designed so that it determines not only an efficient allocation but also a fair, effective, and sustainable distribution of the vaccine. For the users' convenience, the dashboard is divided into different parts that include the input parameters (e.g., the supply of vaccine, the distance from the central stoarge to the municipalities, the number of unvaccinated people etc.), decision variables (the number and type of the vaccines), and outcomes (the vaccination rate in municipalities and or priority groups). The extended and proposed dashboard has been presented and discussed with the CONTRA team and the advisory board during the project meeting in December 2021. A vital characteristic of the proposed DSS and mathematical model is that the policymakers can apply it in middle and low-income countries with some alteration.

The project team agreed to complete the following next step: finalizing dashboard design, continuing iterative process for the dashboard (user-centric), testing and validating dashboard (components, usability, accessibility, etc.), and finalizing DSS documentation.

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