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Decision making on allocation of Covid-19 Vaccines in Africa

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List of abbreviations

AHP	Analytic Hierarchy Process
AMC	Advance Market Commitment
COVAX	Covid-19 Vaccines Global Access Facility
COVID 19	Coronavirus disease 2019
ECDC	European Centre for Disease Prevention and Control
HSC	Health System Capacity
LPI	Logistic Performance Index
RAM	Resource Allocation Model
Sars-cov-2	Severe acute respiratory syndrome coronavirus-2
SMART	Simple Multi Attribute Rating Technique
WHO	World Health Organization

List of symbols

Be_{HI}	Beds in hospital and intensive care units
$B_{not\ scaled}$	Value of benefit for package, not scaled
B_{scaled}	Value of benefit for package, scaled 0-100
B_{R_S}	Value of benefit for the used strategy in considered region
C_T	Transport costs
C_w	Warehouse costs
c	Number of encounters of people in one unit of time
d	Period of being contagious
H_C	Health System capacity
r	Probability of transmitting a virus while having contact to a person
$P_{country}$	Population of considered country
P_R	Population of considered region
$PD_{average}$	Average population density of considered region
$PD_{country}$	Population density of considered country
PD_{scaled}	Scaled population density on a scale of 0-100 for considered region
P_{total}	Total Population of considered region
R	Reproduction value
$R_{average}$	Average Reproduction value of considered region
$R_{country}$	Reproduction value for considered country

R_{scaled}	Scaled reproduction value on a scale of 0-100 for considered region
$R_{weighted}$	Weighted Reproduction value of considered country
S_R	Strategy as a decimal percentage of considered region's population
$T_{individual}$	Individual value of benefit for the category threat for considered region and strategy
$T_{common\ scale}$	Value of benefit for the category threat for considered region and strategy on a common scale of 0-100
T_{scaled}	Individual value of benefit for the category threat for considered region on an individual scale of 0-100
V_{S_R}	Value of vaccine doses of considered strategy for a given region in thousands
$w_{B_{HI}}$	Weight of beds in hospital and intensive care units
w_{C_T}	Weight of transport costs
w_{C_w}	Weight of warehouse costs
w_{H_C}	Weight of Health System Capacity
w_{PD}	Weight of population density
w_R	Weight of reproduction value
w_T	Weight of threat
X	Amount of vaccine doses
Y	Value of benefit for considered package

1. Introduction

1.1. Objective of The Study

The COVID-19 pandemic has overwhelmed health systems and hugely influenced economies around the world. An effective and efficient control can only be reached through sustained public health measures and equal access of populations at different income levels to affordable, safe and assured quality vaccines among other health products (WHO, 2020, p. 5)

The fast track development of Covid-19 vaccines was a great success of modern science, however there have been justified fears that richer countries could hoard the vaccines at the expense of poorer ones. Highlighting inequalities in January, the World Health Organization's (WHO) head said that more than 39 million doses had been administered in at least 49 higher-income countries, but only 25 in one of the lowest-income countries (BBC, 2021). Therefore an ambitious international scheme called Covax (Covid-19 Vaccines Global Access Facility) aims to make sure vaccines are shared among the poor and rich countries equally. It was launched in April 2020 and is led by the WHO, together with the Global Vaccine Alliance and the Coalition for Epidemic Preparedness Innovations.

A total of 92 low- and middle-income countries and economies will be able to access COVID-19 vaccines through Gavi's Covax Advance Market Commitment (AMC) (Gavi, 2020).

At the first phase of the distribution of vaccines to member countries, Covax aims to vaccinate 20% of all country's populations. Once 20% of population per country is covered (i.e. Tier 1), Phase 2 of the allocation process will gradually expand access to cover a larger portion of the population in all countries (WHO, 2020, p. 25).

In this study we use the framework of the aforementioned organization to create strategies for allocating resources (vaccine doses) to 3 different regions in Africa because the studies show that cases of the pandemic vary geographically across Africa with notably high incidence in neighboring countries (Ezra, 2020, p. 5). Therefore, regions have to be prioritized for vaccination rather than countries alone. From this point of view, the problem was considered as a resource allocation problem and the regions were prioritized according to their threat level, health system vulnerabilities and logistics costs. In our model we created 3 different strategies as to address the needs and weaknesses of relative regions. These strategies include the vaccination of a) 10%, b) 20% or c) 30% of a region's population. The inclusion of any of the mentioned strategies in a package of chosen strategies would result in certain levels of resource allocation and relative benefits arising thereof, which are analyzed in detail in the report.

In the end we will show the results of the study in the form of an efficient frontier, containing the strategic packages. With this efficient frontier we can always see the best packages given a specific amount of resources.

1.2. Structure of The Report

First of all, the theoretical background is described in this paper. To understand why we have chosen the continent Africa for the COVID-19 vaccine allocation, it is necessary to have an overview of the current status in Africa according to the actual COVID-19 situation. Afterwards the Covax approach towards low- and lower-middle income countries will be explained, which will be easier to understand due to the actual COVID-19 status in Africa.

Then we will compare different decision analysis methods to show their abilities and constraints. The comparison will show, based on which criteria we chose our decision analysis model and why we selected the Resource Allocation Model for the Allocation of COVID-19 vaccine in Africa. Subsequently the steps of the Resource Allocation Model will be explained shortly.

The main part of this paper will be the following chapter 4 “Method Execution” in which the Resource Allocation Model is applied and which shows how we have worked out our solution to the problem with the help of the Resource Allocation Model. First it is stated how we determined the given resources and benefits and the areas which will be considered in the resource allocation. Second the possible strategies for the resource allocation and third the assessment of resources and the related benefits will be shown. In the fourth part the within-criterion and the across-criteria weights will be discussed.

In the fifth chapter the results will be explained and presented in the form of an efficient frontier. Finally, the conclusion will be made with a short summary and an overview of the limitations of our results regarding the COVID-19 vaccine allocation in Africa.

2. Theoretical Background

2.1. COVID-19 Status in Africa

After 2002 & 2012, a new severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2) has emerged. The SARS-CoV-2 caused an infectious disease 2019, called COVID-19, which was first identified in the Chinese city Wuhan, in December 2019 (Lone and Ahmad, 2020, p. 1300). The highly contagious virus reached the continent Africa on 14th of February 2020, when the first case of COVID-19 was confirmed and reported in Egypt. COVID-19 spread globally very fast and was declared a global pandemic by the World Health Organization in March 2020 (Lone and Ahmad, 2020, p. 1300).

The pandemic harmed low- & lower-middle-income countries more than high income countries. Also, Africa was expected to be more vulnerable compared to other continents due to Africa's weak health care system and the large immunocompromised population with lots of malnutrition, anemia, malaria, HIV/AIDS and tuberculosis and Africa's poor economic discipline (Lone and Ahmad, 2020, pp. 1300, 1301).

According to the WHO Regional Office Africa, in the past one year, over 3.7 million COVID-19 cases and almost 100.000 deaths due to the virus have been reported in Africa (Adebowale, 2021). The national economies, livelihoods and developments of the African countries suffered under the pandemic and the health systems in many countries are very overstressed. Furthermore about 20 million jobs in Africa are at risk and the pandemic has triggered, or rather more, caused Africa's first recession in 25 years (Adebowale, 2021).

2.2. Covax allocation approach

As discussed in the concept for fair access of COVID-19 pandemic health products (WHO, 2020, p. 10), WHO suggests that the overarching goals of protecting individuals and health systems and the minimizing impact on societies and economies should be the guideline for the allocation process of COVID-19 health products. In a logical scenario with the major focus on mortality reduction and protection of the health system, the next step is the identification of corresponding target groups to maximize the effect with limited supply. First to notice an average vaccination of 3% of a population would be enough to cover all workers in the health and social care section. Moreover, for most of the countries, an allocation including 20% of the population would be sufficient to cover most of the population, comprising initially prioritized target groups (frontline workers, people over the age of 65 years, people with underlying conditions that put them at a higher risk of death) (WHO, 2020, p. 25).

According to WHO in case of severe supply constraint, the allocation of vaccine doses will undergo adjustments using the weighted allocation. The prioritization and determination of supply pace of products at this phase should be based on a risk assessment through the evaluation of: threat (the potential impact of COVID-19 on a country, assessed using epidemiological data) and vulnerability (the vulnerability of a country based on health systems and population factors). Furthermore, we take logistics cost into consideration as to give logistics difficulties of every region a weight in our model.

3. Methodical Approach

3.1. Selection of decision analysis methods

First of all, we wanted to find a decision analysis method to distribute the vaccines to three different regions. Therefore, we compared the MCDM techniques AHP, Even Swap, SMART and the Resource Allocation Model with each other: The Even Swap method provides an opportunity to make trade-offs across any set of objectives across lots of alternatives (Hammond et al., 1998, p. 3). At the end of the decision process only one objective remains on the basis of comparison to the other objectives (Hammond et al., 1998, p.7). This method is a simple way to solve a problem but also, on the other hand, not detailed and objective, because the decision makers value and eliminate objectives (Hammond et al., 1998, p.7).

The Simple Multi Attribute Rating Technique (SMART) is used, “when a particular course of action is regarded as certain to lead to a given outcome” (Goodwin and Wright, 2004, p. 28). It is simple and transparent and consequently makes a problem easy to understand for the decision makers, but it doesn’t consider all the details and complexities of a real problem (Goodwin and Wright, 2004, p.30).

The Analytic Hierarchy Process (AHP) is the most robust, objective and detailed decision method in comparison to Even Swap and SMART. For this method decomposes a complex decision problem into its components and models it in a hierarchical structure (Gussek, 1991, p.161). It is an alternative to SMART, because the AHP is suitable if the decision maker is faced with a problem involving multiple objectives (Goodwin and Wright, 2004, p.413). But also, with the AHP method, there can be selected only one and the best objective, in our example, the best region (Goodwin and Wright, 2004, p.420).

Since all the named methods (AHP, Even Swap and SMART) provide solutions, in which the distribution is made to only one region, the Resource Allocation Model proves to be the most suitable decision analysis method for our decision problem. The Resource Allocation Model (RAM) is a method for the allocation of a limited resource between several alternative uses (Goodwin and Wright, 2004, p.229); in our case it would be between several alternative regions in Africa.

3.2. Resource Allocation Model

There are 9 stages in the decision analysis method for the resource allocation problem according to Goodwin and Wright. The first stage deals with the identification of all important aspects of the resource allocation problem. It is separating between resources, variables and benefits. The resource is giving this decision analysis problem its name. It is that aspect, which is going to be allocated based on the benefits and the possible variables. The variables indicate areas where the resource can be allocated to, while the benefits are aspects which are hoped to be achieved during the allocation and may differentiate in terms of impact regarding the strategy (Goodwin and Wright, 2004, p. 331).

The second stage of the Resource Allocation Model deals with the identification of the possible strategies within each region. In this stage each variable is analyzed considering in which way a strategy can be applied on it. It is important that each strategy is connected to a resource usage. So, a strategy which has nothing to do with the resource which is to be allocated, is not a valid strategy in this model. This usage can be negative as shown by Goodwin and Wright when there was an example of negative investment costs. The important aspect is that the strategy was linked with the resource in some way (Goodwin and Wright, 2004, p. 331).

The third stage of the allocation model deals with the assessment of the costs and the benefits for each strategy in each region. The costs are referring to the resource and can be as mentioned earlier negative. It is also important to mention that costs do not have to be monetary. They can be of any nature. The benefits need to be measured in a way or estimated in this stage (Goodwin and Wright, 2004, p. 331).

Stage 4 of this decision analysis model claims that each benefit can be measured on a common scale. This is called the within-criterion weighting. It is important in order to compare the impact of each benefit and relativate the different strategies (Goodwin and Wright, 2004, p. 331).

Stage 5 is dealing with the across-criteria weighting. In this stage all the benefits are compared with each other and it is stated how important each of them is. They are all placed on an overall benefit scale so that it is visible, which benefit and with which percentage it is more important compared to another one. All the benefits types combined should add up to 1 or 100% (Goodwin and Wright, 2004, p. 331).

Stage 6: Since we know the weights of each benefit, the assessment of the benefits and the costs, we can now calculate packages. A package contains a strategy for each variable and shows how much benefit it will achieve and how many resources need to be allocated for this benefit. It is recommended that a computer does the calculation for the benefits. Furthermore, an efficient frontier should be seen when creating a graph. On this frontier the most preferable packages are shown (Goodwin and Wright, 2004, p. 332).

Stage 7 and 8 deal with the proposition of the right packages. These packages should be within the restriction e.g., a limitation of cost of resources, and it should be made sure that there are no better packages to choose. In other words, they should correspond to the trade-off which was made (Goodwin and Wright, 2004, p. 332).

Stage 9 recommends a sensitivity analysis. One stage here is to think if other packages are more preferable even if more resources need to be allocated and the second step is to rethink about the data which are used in this model. That includes the assessment of the benefits and the across and within scores (Goodwin and Wright, 2004, p. 332).

4. Method execution

4.1. Determination of resources, areas and benefits

The first stage of the Resource Allocation Model is to identify the resources which are to be allocated, the regions or destination (variables) to which they can be allocated and the achieving benefits which result from the allocation (Goodwin and Wright, 2014, p. 331).

In our case the determination of the resource is very simple. Since the main focus of this paper lies in the allocation of vaccines to the countries or regions which need it the most, our resource is vaccines. As mentioned earlier, with that decision we can always estimate the best variables combination when setting a specific amount of vaccine allocation. In the following paper, when we speak about the distribution of vaccines in Africa, we refer to the low- and lower-middle income countries in Africa only and not Africa as a whole continent.

Figure 1: African regions

The decision of our variables was clear too. Our topic deals with the vaccine distribution in Africa so the variables are regions in Africa. We also came to the conclusion that the regions should be grouped geographically in one area and not set by other characteristics like accessibility. This decision is set by the assumption that the virus spreads from one country to another (Ezra, 2020, p. 5). With the distribution to regions and not countries alone, we assume that the virus spread can be more contained. Furthermore, we tried to create regions, which should be equal with the remaining regions in terms of population, area and border lengths of the region to another region. We did that in order to keep the comparability high. The last restriction was that one country should be fully assigned to one region, because in reality it will be hard to justify why one part of a country is getting more vaccines than another part of the same country. Also, calculation and research-wise it is difficult alone to find data for some African countries, not to mention specific areas in those countries.

We started building up regions in southern, western and eastern Africa, since we were sure that we have at least three regions. Mozambique, Egypt and Senegal would be in different regions because of the distance between all three countries. Then, we enlarged each region with more and more countries. We were sure that some countries should be assigned to a specific region because of their position or the impact of being in another region. A good example of those cases are the Democratic Republic Congo and Mali. If they were assigned to Region East for example, then the border to the current regions would be extremely large. At the end, we had three regions and we only had to assign Chad, Cameroon and the Central African Republic to a region. Since Region West was already the largest in terms of population, we could exclude this region out of our discussion. Region East's population was the smallest at this point, so we assigned the countries to this region.

Our final decision about the regions can be seen in figure 1. The red region is in the western part of Africa, the green region is located in the eastern part of Africa, while the blue region is located in the south of Africa. It should be mentioned that Comoros is part of Region South, Sao Tome and Principe is part of Region East and Cape Verde is assigned to Region West.

4.2. The benefits

In our case we have five different benefits. The benefits are costs for transportation, costs for warehousing, threats, Health System Capacity (HSC) and occupancy of hospitals. As much as the vaccination of the African population is important, costs are also a significant determinant for the decision analysis. Overall, a distribution operation has to be economically sustainable and the subsidy or funds for the operation are limited and therefore costs are also to be calculated and discussed. We distinguish between transport and warehouse costs. They are both increasing when more vaccines are delivered, but the difference of the increase might change. Less costs resolve in a higher benefit than a higher amount of costs. In the following, warehousing costs are called warehouse costs and costs for transportation are called transport costs.

The criteria of vulnerabilities were divided into two benefits of Health System Capacity and status of hospital & intensive care unit beds. This benefit aims to prioritize countries that are at increased risk due to weaknesses in their health system. Two analyses will be used to assess such vulnerability: (1) the Health System Capacity according to the universal health coverage index, and (2) the occupancy of hospital beds (WHO, 2020, p. 32)

Furthermore, not all of the countries are affected equally by the pandemic and due to this, it is necessary to assess the current situation and the factors that influence the pandemic development. Looking at the factor threat, using the R-value and population density, allows us to measure how critical the COVID-19 situation in every region is and the need for vaccination accordingly (WHO, 2020, p. 27). The need for vaccination in a region, represented as a threat is used as a benefit in this study. This means that regions having a higher threat value will be preferred to receive vaccinations.

4.3. Identification of possible strategies

According to the WHO an amount of doses representing 3% of the population are needed to vaccinate all employees in social and health care systems (WHO, 2020, pp. 24-25). In our group we discussed whether to take this 3% as a strategy or not. We concluded that our aim is to provide vaccinations for more than just medical and social care staff and that we are also able to provide more than 3% in doses with the first delivery. Following this we increased that number to 10%. This would cover the employees in health and social care systems, as well as a part of other risk patients like people over 65 years and people with other health issues. The employees in the health and social systems are important as they take care of infected people, they are in contact with the virus or take care of people classified as a risk group (WHO, 2020, p. 24). Furthermore, people aged over 65 years and people having a bad health condition are facing a higher risk of dying, have a more severe infection and consequently increase the burden on the Health Care System (ECDC, 2020, p.4). Until December 2020 95% of COVID-19 deaths in Europe were people aged 60 years or older (ECDC, 2020, p.4). Looking at these factors, it was very important to us to reach more than 3% of the population with the first delivery and we took the number of doses representing 10% of the population as strategy 1.

According to the WHO, a number of doses that covers 20% of the population, would be sufficient to cover most of the risk groups concerning health and social care workers, people aged over 65 and people having health conditions that increase the risk of death due to a COVID-19 infection (WHO, 2020, pp. 24-25). Following this, we agreed to take 20% as strategy 2.

Furthermore, the WHO suggests that a coverage with vaccines of more than 20% of the country's population would allow to vaccinate additional groups that are not classified as risk patients, medical staff or care workers (WHO, 2020, p. 25). Discussing in the group it seemed reasonable for us to take 30% as strategy 3, being able to vaccinate other target groups as well and having three equally spaced strategies. Strategy 1 as being 10%, strategy 2 as being 20% and strategy 3 as being 30% of the region's population receiving vaccinations.

Also, a higher number than 30% seemed to be unachievable within a certain time frame due to production time, limited availability of vaccines and distribution to other countries in different continents as well. We thought that other countries in the world needed to be treated equally and also receive parts of the vaccine. As a conclusion we set 30% as our highest strategy.

5. Assessment of resources and benefits

5.1. Resources

Stage 3 in the Resource Allocation Model dealt with the assignment of the costs and benefits for the different strategies in each region as mentioned by Goodwin and Wright," For each variable, assess the costs and benefits of the different strategies" (Goodwin and Wright, 2014, p. 331). The aspect of costs in relation to the Resource Allocation Model is referring to consumption or the number of used resources. In our case we will call this kind of cost simply "Needed Resource" in order to avoid confusion with the benefits transport costs and warehousing costs. Since our strategy is to vaccinate 10%, 20%, or 30% of the population in each region, the amount of Needed Resource can easily be calculated. The multiplication of the amount of people in each region and the percentage of each strategy will show the demand of Needed Resource. It is important to mention that we assume that 1 vaccine dose is used for one person and each vaccine dose, which is going to be delivered, will also reach its destination in a good quality so that a person can get vaccinated. The population in each region is shown in table 1: Region's Population. The resource costs are shown for each strategy and region in table 2: Needed Resource per Strategy.

Table 1: Region's populations (thousands)

	Region West	Region East	Region South
Population	494,438	340,789	427,529

Table 2: Needed Resource per Strategy

Region West	Needed Resource (thousand doses)	Region East	Needed Resource (thousand doses)	Region South	Needed Resource (thousand doses)
Strategy 10%	49,443.80	Strategy 10%	34,078.90	Strategy 10%	42,752.90
Strategy 20%	98,887.60	Strategy 20%	68,157.80	Strategy 20%	19,777.52
Strategy 30%	148,331.40	Strategy 30%	102,236.70	Strategy 30%	128,258.70

5.2. Costs

Two of the benefits in our model are categorized as costs. As mentioned earlier, we are distinguishing transport costs from warehouse costs. The transport costs are getting affected by the macro logistic environment. An example could be bad road conditions compared with good road conditions. The transportation on a bad road takes longer and may not be passable at all for some time, which results in an increase of costs. The first step, in order to find values for the costs, is to calculate the overall macro logistic performance in each region. After that, we give one region's strategy a value. When we know the overall macro logistic performance in each region, we have an idea how that value might be different compared to the other regions and other strategies. In regions with good logistic performances, this value is not increasing as much as in regions with a bad performance.

In this paper the macro logistic performance of a region is defined by the LPI-Transport-Index. This index consists of the LPI and a Transport Index. The transport index is calculated in this paper by four factors, which are road condition, port condition, airport condition and rail condition of each country. There is a weight of 60% for the airport performance, because we think this is the most important infrastructure when it comes to vaccine delivery. Vaccines might have to be delivered fast and regions in central Africa may be difficult to reach without a plane and therefore we came up with this weight. The last mile or the transportation from the airport to the final destination is important too, so we placed a weight of 20% upon it. One-third of the importance of the airport seemed reasonable for our group. The remaining factors got a weight of 10%, because they might be good in some cases and needed for countries like Comoros which consists of islands only, but the other two factors are far more important than those infrastructure aspects.

$$Transport\ Index_c \ = 0.2 * Score\ Road_c + 0.1 * Score\ rail_c + 0.1 * Score\ port_c + 0.6 * Score\ airport_c$$

The next step is to find the weighted average Transport Index score for each region. This score is simply called Transportation Index. The calculation is shown in the formula below. The weighted Transportation Index for a country can be calculated by multiplying the score with the ratio from the country to the region's population where the country is located. The Transportation Index for a region can then be calculated by getting the sum of all country weighted Transport Indexes in a region.

$$Transportation\ Index_{region} = \sum Transportation\ Index_{weighted}$$

$$Transportation\ Index_{weighted} = Transportation\ Index_{country} \frac{Population_{country}}{Population_{region}}$$

The warehouse costs get affected by the temperature in the countries. There haven't been reliable sources for power shortages, so this aspect could not be taken into consideration, since there was no information for the majority of the countries. In this paper, because of the temperature, the warehouse costs are different in the regions. A higher temperature leads to higher warehouse costs, because the vaccine needs to be cooled down (Jocelyn Kaiser, 2020). The calculation of the warehouse costs starts by gaining information about the average temperature in each country. After that a weighted average is used in order to find the average temperature in each region. The weight is the amount of the country's population from the total population in the considered region. You can see this formula below. After calculating each temperature average a country's strategy gets an assigned value. With the knowledge about the average temperature, we can now assign values for the remaining strategies and regions by thinking how much more this value would be in the different strategies and regions.

$$Warehouse\ Cost_{region} = \sum Warehouse\ Costs_{weighted}$$

$$Warehouse\ Costs_{weighted} = Warehouse\ Cost_{country} \frac{Population_{country}}{Population_{region}}$$

The source for the temperature is the World Bank Data Catalog and every country is listed there with the average temperature from 1961-1990. We chose this time span, because the data is the most reliable one and some countries were missing on later dates or multiple sources gave different temperatures for time spans in the 2010s. Note that South Sudan is not listed on this website, because it became independent in 2011 (UN, 2011). The country got its independence from Sudan and therefore the same temperature is used for South Sudan (BBC, 2011). For the Transport Index three different sources were used. First, TheGlobalEconomy which gave data for many countries. The same goes for the WorldEconomicForum. The last source is a research done by us and all the sources for this research can be seen in annex 3. The scale for the transport related information lies between 1-7 while the temperature is measured in Celsius. The source for the LPI was the World Bank's website and provided information for almost all countries (WorldBank, 2019).

The data got collected and is shown in 3. Sources marked with [A] are from TheGlobalEconomy, sources marked with [B] are from WorldEconomicForum, sources marked with [C] are the average from both sources when there was data about a country's logistic performance from both sources. Cells marked with [D] show a performance which was assigned by us. We searched through multiple websites, blocks, encyclopedias, google maps and street view to give the missing country in [D] a score. We did that by searching for some country's performances marked with [A], [B] or [C] and compared the information so that we could get some reliable scores and consequently, the transport index was calculated. The LPI score for each region was calculated by first listing all the LPIs for each country and then calculating the weighted average for each region, where the weight is the region's population. In Table 3 you can see the Transport Index for each region, the LPI for each region and the temperature. The LPI-Transport-Index is calculated by normalizing the Transport Index and the LPI. The LPI's range is from 1-4.2 and the Transport Index is from 1-7. At the end the Transport Index is being valued twice as much as the LPI, because the main focus lies in the quality of the macro logistic environment. The LPI is used because there are some factors in how to use the transportation methods and they are somehow shown in this LPI, that is why the LPI is used too. An LPI-Transport-Index of 100 would mean that the Transport Index lies at 7 while the LPI would lie at 4.2. A score around 50 means that the score is just half as good as the maximum.

Table 3: Temperature/LPI-Transport-Index

	Transport Index	LPI	Temperature	LPI-Transport-Index
Region West	3.25	2.50	25.66	50.78
Region East	3.44	2.53	23.64	52.88
Region South	3.28	2.57	22.76	51.63

The following part deals with the assessment of the benefits of transport costs and warehouse costs for each strategy. First, the transport costs are explained, then the warehousing costs. The transportation strategy 1 in Region West got the cost value of 10. The number is random. The important part is that the following costs are relative to the ten costs. This model requires to measure the benefits in a normalized scale from 0 to 100, so the nominative difference is not important, the relative is. Since Region South has a better LPI-Transport Index score, the first strategy costs 9 only so a unit less than in Region West. Region East is even better than Region South, so we assigned the value 8 for the strategy one. Then for strategy 2 we doubled the value of strategy 1 and reduced it by 1. We do that, because it's likely that the transportation gets more efficient with a larger quantity. Transportation can be used more efficiently and therefore the costs are getting reduced. For strategy 3 we used strategy's 2 value and added strategy's 1 value + 1 into the calculation, because from 20 to 30% we assume that there could be inefficiencies in the transport, which would raise the transport costs again. The numbers then got used to calculate the normalized scores.

For the warehousing costs we started with a cost value of 10 for Region West's strategy one. Region East was cooler so we reduced the starting costs by one and for Region South, which was even cooler, we reduced it by one more unit. Now we doubled strategy's 1 costs for strategy 2 and added an additional cost on top of it. We think with receiving more vaccines, some vaccines need to be cooled down longer, because it might not get used right away, therefore the costs are rising disproportionately high. For the 30% strategies we added strategy's 1 cost plus 2 additional units, because we think the effect mentioned in strategy 2 gets even bigger. We then used those calculated values to calculate the normalized scores. Both Costs and normalized costs are shown in Table 4.

Table 4: Values of the strategies for costs in the individual regions

	Strategies	Transport Cost	Warehouse Cost	Transport Cost Normalized	Warehouse Cost Normalized
Region West	Strategy 1 (10%)	10	10	100	100
	Strategy 2 (20%)	19	21	55	52,17
	Strategy 3 (30%)	30	33	0	0
Region East	Strategy 1 (10%)	8	9	100	100
	Strategy 2 (20%)	15	19	56,25	52,38
	Strategy 3 (30%)	24	30	0	0
Region South	Strategy 1 (10%)	9	8	100	100
	Strategy 2 (20%)	17	17	55,56	57,14
	Strategy 3 (30%)	27	29	0	0

5.3. Vulnerabilities

Covid-19 like any other pandemic would stress system vulnerabilities and can significantly put the provision of essential care in danger. This criterion aims to prioritize countries that are at increased risk due to weaknesses in their health system. Two analyses will be used to assess such vulnerability: (1) the Health System Capacity according to the universal health coverage index, and (2) the occupancy of hospital beds (WHO, 2020, p. 32).

The considered indicator to measure health systems' capacity is the universal Health Service Coverage (HSC) index which combines several indicators of service coverage into a single summary measure. The tracers include reproductive, maternal, newborn and child health, infectious diseases, noncommunicable diseases, and service capacity and access, among the general and the most disadvantaged population (WHO, 2019, pp. 108-112). As to simplify the use of the HSC indicator for our Resource Allocation Model, we reversed the values to better reflect the indicator as a benefit. The HSC indicator in our model therefore is measured on a scale of 0.01-1. 0.01 would represent the country with the strongest Health Care System and 1 the country with the weakest Health Care System. That means a country with the score of 1 has the greatest need for a vaccine while 0.01 is more resilient. Because in that case the prioritization of the proposed country (region) would be beneficial against the pandemic and from the viewpoint of our model.

On the other hand, considering the limited intensive care unit capacity in low and lower-middle income countries, a combination of assessing occupancy of both hospital and intensive care unit beds is provided to estimate health systems' vulnerability dynamically (WHO, 2020, p. 32). Like in the case of the HSC indicator above, a scale of 0.01-1 was introduced, where 0.01 would represent the country occupying the most hospital and intensive care unit beds and 1 would be the country (region), which is mostly in need of support, hence beneficial for our model. Annex 1 shows the detailed values for vulnerability indicators.

Next based on the findings of the analysis of the indicating data (Annex 1), we discussed the strategies in every region and the desirability of using each of the strategies was assessed in relation to each two identifying indicators of vulnerability. To do this, a value scale which ranged from 0 to 100 was used with 0 representing the least desirable effect and 100 the most desirable. We first discussed the perceived value of each strategy for any given region, regardless of other regions. Table 5 shows the scores for strategies.

Table 5: Values of the strategies for vulnerabilities in the individual regions

	Strategies	Health System Capacity	hospital and intensive care unit beds
Region West	Strategy 1 (10%)	0	0
	Strategy 2 (20%)	70	80
	Strategy 3 (30%)	100	100
Region East	Strategy 1 (10%)	0	0
	Strategy 2 (20%)	60	70
	Strategy 3 (30%)	100	100
Region South	Strategy 1 (10%)	0	0
	Strategy 2 (20%)	60	60
	Strategy 3 (30%)	100	100

5.4. Threat

According to the WHO the threat is the effect that COVID-19 has on a country and is measured with epidemiological data (WHO, 2020, p.25). Since not all of the countries are affected equally by the pandemic, it is necessary to evaluate the current situation and other factors that influence how the pandemic evolves (WHO, 2020, p. 27). The countries, or in our case regions, having a higher risk shall receive more vaccines compared to the ones with lower risk. The WHO suggests to consider two factors concerning threat level (WHO, 2020, p. 27).

The first factor is the so-called R-value (the effective reproductive number). The R-value is a value that measures the number of people that get infected by one infected person over the period of his or her infection (Annunziato and Asikainen, 2020, p.6). The reproduction number is calculated by using the formula $R = r \cdot c \cdot d$, with r being the probability of transmitting the virus while having contact to a person, c being the number of encounters of people in one unit of time and d being the period of being contagious (Annunziato and Asikainen, 2020, p.6). Judging by this information, a number above one means that the cases of Corona viruses are increasing and below one means a decrease of new corona cases.

The second factor is the appearance of influenza viruses. According to the WHO this will influence the testing capacity, be an additional workload for the health care system and increase the risk for risk patients like elderly (WHO, 2020, p. 31). We tried to gather information regarding the influenza infections in the low- and lower middle-income countries in Africa. Unfortunately, the data basis for these influenza infections was not detailed enough for us to be able to use this data in our model. It was not possible to get information for many countries. Some countries were either not listed in the source, contained an unreliable value of zero infections throughout the year or had quite high numbers of positive influenza tests compared to others. This made us in the group conclude that countries are not testing equally regarding influenza, not having a good healthcare system for testing or people not being insured or connected towards the health care system (Appiah, 2012, p.125-126). Due to this reason we decided to exclude this variable and use the population density instead. A study from Li, Richmond and Roehner proved a relationship between the death rate of epidemics and population density with lower density having a lower death rate (Li, Richmond and Roehner, 2018, p. 12-13). Also, the study of Tarwater and Martin confirmed that a higher population density increases the number of transmitted diseases (Tarwater and Martin, 2001, p. 35). This makes the population density a good indicator for the transmission of diseases in general and also for the circulation of viruses like influenza that are an additional risk factor for risk patients and a burden for the healthcare system.

For finding the right values of the general strategies in each region, we had to assess the benefits for each strategy. According to Goodwin and Wright we have to use a scale ranging from 0 to 100 with giving 0 for the strategy with the least benefit and 100 for the strategy with the highest benefit in each region (Goodwin and Wright, 2000, pp. 320-321).

In a group discussion we concluded that strategy 1 would bring the least benefit with the lowest amount of doses for the country and therefore getting the benefit value of $T_{individual}$ = 0. The value of zero symbolizes that this strategy will help the least against the threat or spread of COVID-19. Strategy 3 on the other hand brings the highest benefit due to receiving the most vaccine doses and gets assigned the value of $T_{individual}$ = 100. After this we had to think about a value for strategy 2. The rate of change from Strategy 1, where 10% of the population receives a vaccine, to strategy 2, where 20% of the population receives a vaccine, is 200%. The change from strategy 2 (20%) to strategy 3, where 30% of the population receives a vaccine, is just 150%. Comparing the rate of changes, the change from strategy 2 to 3 is 50% less than from strategy 1 to 2. Taking this into account, we came to a benefit value in the category threat of $T_{individual}$ = 67 for strategy 2. The change from 67 to 100 is 33 and 50% of the rate of change of strategy 1 to 2. Also, it seemed to be more important to vaccinate the risk groups and staff in hospital and care units first. Until December 2020 95% of COVID-19 deaths in Europe were people aged 60 years or older (ECDC, 2020, p.4). Looking at these factors and transferring it to Africa, we decided to give strategy 2 five extra points due to the importance of achieving a 20% vaccinated population, adding up to a total of 72 for $T_{individual}$. Since inside the individual regions the benefits of each strategy are the same, we decided to give them all the same values. All $T_{individual}$-values can be found in table 6.

Table 6: Values of the strategies for threat in the individual regions

	Region West	Region East	Region South
Strategy 1 (10%)	0	0	0
Strategy 2 (20%)	72	72	72
Strategy 3 (30%)	100	100	100

5.5. Results

In the preceding sections we calculated the individual benefits for each region and strategy. The results are summarized in table 7. The benefits are divided into costs, threats and vulnerability with a subdividing of costs into transport and warehouse costs and vulnerability into Health System Capacity and Hospital and intensive care unit beds.

It is visible that in terms of costs, strategy 1 is the best in each region, while threat and vulnerability (HSC and Hospital and intensive care unit beds) recommend strategy 3 for each region, with the amount of resources needed increasing from strategy 1 to 3.

Table 7: Values of the strategies for Needed Resources and benefits

Strategies	Needed Resource (thousands)	Benefits				
		Transport costs	Warehouse costs	Threat	Health System Capacity	Hospital and intensive care unit beds
Region West						
Strategy 1	49.444	100	100	0	0	0
Strategy 2	98.887	55	52,17	72	70	80
Strategy 3	148.331	0	0	100	100	100
Region East						
Strategy 1	34.079	100	100	0	0	0
Strategy 2	68.158	56,25	52,38	72	60	70
Strategy 3	102.237	0	0	100	100	100
Region South						
Strategy 1	42.753	100	100	0	0	0
Strategy 2	85.506	55,56	57,14	72	60	60
Strategy 3	128.259	0	0	100	100	100

6. Within-Criterion /across-criteria Weights

6.1. Costs

The starting point in order to calculate the within-criterion weights for the transport and warehouse costs is table 4 shown in the previous chapter. We can simply use the numbers in order to immediately calculate the within-criterion by setting the range of the costs for transport costs from 8 to 30. For warehouse costs the range reaches from 8 to 33. We use this formula to calculate every within score. If we look at the within transport cost for Strategy 2 in Region West, we can see that it got the score of 50. This is the case, because the value for cost of 19 is in the middle between the lowest value of 8 and the highest value of 30 for cost. The table 8 shows again the Costs for each Strategy and the relative within Score for each county.

$$Within\ Score = 1 - \frac{Costs - Lowest\ Cost}{Highest - Lowest\ Cost}$$

Table 8: Costs Benefits considering within-criterion weights

	Strategies	Transport cost	Warehouse cost	Within transport costs	Within warehouse costs
Region West	Strategy 1 (10%)	10	10	90,91	92
	Strategy 2 (20%)	19	21	50	48
	Strategy 3 (30%)	30	33	0	0
Region East	Strategy 1 (10%)	8	9	100	96
	Strategy 2 (20%)	15	19	68,18	56
	Strategy 3 (30%)	24	30	27,28	12
Region South	Strategy 1 (10%)	9	8	95,46	100
	Strategy 2 (20%)	17	17	59,09	64
	Strategy 3 (30%)	27	29	13,64	16

6.2. Vulnerability

As to include the importance of strategies for each region, we calculated the within-criterion weights of attributes in different regions by discussing our findings in group meetings and by further analysis of the Health system vulnerabilities in Africa (WHO, 2019, pp. 108-112). As a result, the common scale for both attributes of HSC and Hospital and intensive care unit beds would be the western region in Africa, meaning the movement from the worst strategy to the best in the west would result in the highest benefits in the west and the other regions can be compared on that main scale. (Figure 2 and Figure 3)

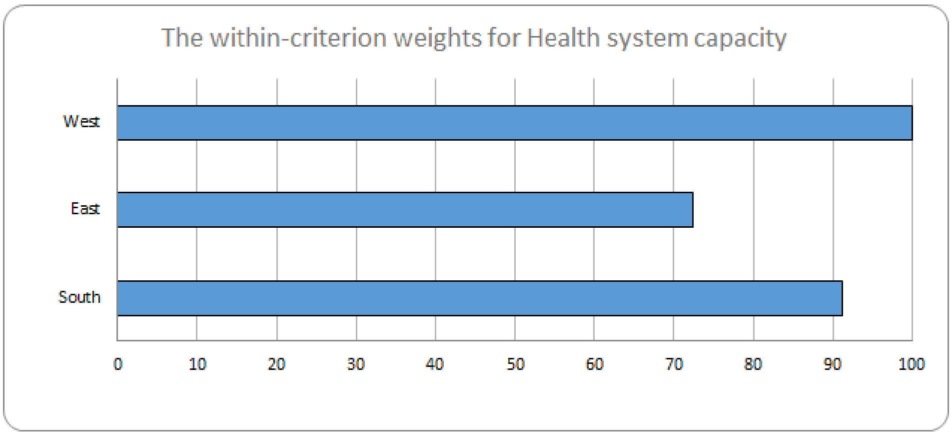

Figure 2: The within-criterion weights for Health System Capacity

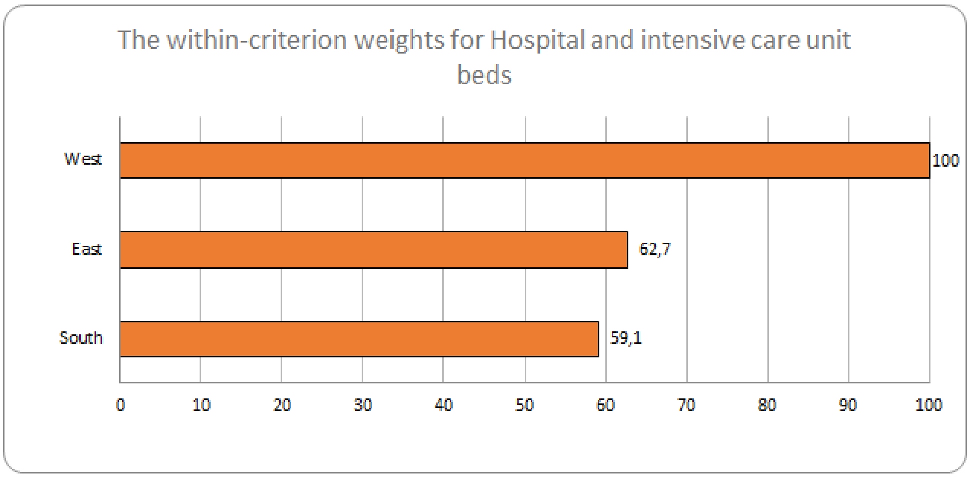

Figure 3: The within-criterion weights for Hospital and intensive care unit beds

Finally, values of the strategies for vulnerabilities in the individual regions were once again revised to contain the within-criterion weight assigned to benefits. As a result, the values for each benefit in every region was measured on the common scale in table 9.

Table 9: Values of strategies with each benefit measured on common scale

Region	Strategies	Benefits	
		Health System Capacity	hospital and intensive care unit beds
West	Strategy 1	0,0	0,0
	Strategy 2	70,0	80,0
	Strategy 3	100,0	100,0
East	Strategy 1	0,0	0,0
	Strategy 2	43,4	43,9
	Strategy 3	72,4	62,7
South	Strategy 1	0,0	0,0
	Strategy 2	54,7	35,4
	Strategy 3	91,2	59,1

6.3. Threat

Measuring the threat for each region on a common scale, it was necessary to look into the collected data.

Using the databank "Our world in data" made it possible to extract the daily reproduction values for each country. With the goal of starting the distribution at the beginning of 2021, we used the most recent data in December 2020. We collected data reaching from December 01 until December 22, 2020. The period from December 23 until December 31 was excluded due to a possibility of decreased testing during Christmas holidays. We reflected and transferred the situation in Germany, where there was less staff in health care facilities and departments available during the Christmas holidays (Stotz, 2021). Furthermore, people will start travelling, leaving and joining countries with less restrictions being present during that period, possibly falsifying the data (Tamma, Gehrke and Pogatchnik, 2020).

To receive a daily average of the R-value for each country in the period of December 2020, the single R-values were added and divided by the number of values with the result of receiving $R_{country}$. To get then a single value for one region, the reproduction numbers were weighted using the following formula:

$$R_{weighted} = R_{country} \frac{P_{country}}{P_{total}}$$

We used the R-value of each country and multiplied this with the amount of the country's population from the total population of that region. In the end, to get the average for each region, we took the sum of all $R_{weighted}$-values.

$$R_{average} = \sum R_{weighted}$$

Region West has R-values that reach from 0,16 to 1,45, resulting in a weighted average of 1,19. The reproduction values of Region East reach from 0,36 to 1,22 with a weighted average of 1,01. Region South achieves values between 0,31 and 1,57 with an average of 1,04. For Tanzania it was not possible to receive reproduction data and due to this it was excluded in the calculation of $R_{weighted}$ and$R_{average}$. The results are shown in the annex 2.

Using the databank "Worldometers" we extracted the population density from 2020 for each country. Using again the following formula, we received the weighted values and the average for each region as $PD_{average}$. The unit for density in this case were the numbers of people per km².

$$PD_{average} = \sum \left[PD_{country} \frac{P_{country}}{P_{total}}\right]$$

The density in Region West varies between 5 and 239 people per km², resulting in a weighted average of 135 people/km². Region East achieves values reaching from 8 to 228 people/km² with a weighted average of 80 people/km². Region South has values from 16 to 525 people/km², resulting in a weighted average of 104 people/km². All values can also be found in the annex 2

Since we are measuring the threat for each region on a common scale, we projected the values for effective reproduction and population density on a 0-100 scale. To achieve that we set the region with the highest weighted average value to 100. In this case it was Region West for R-value and population density. In general, the scaled values are calculated as followed:

$$R_{scaled} = \frac{R_{average}}{R_{average\ max}} * 100 \qquad PD_{scaled} = \frac{PD_{average}}{PD_{average\ max}} * 100$$

Applying this formula, we receive the value 100 for PD_{scaled} (population density) and R_{scaled} in the Region West. Region South has the second highest values with 88 for R_{scaled} and 77 for PD_{scaled}. Region East achieves values of 85 for R_{scaled} and 60 for PD_{scaled}. These values are also shown in the table of annex 2.

Having these values, the next step was to create a single value for threat, combining the values for reproduction number and population density. For this reason, we weighted the R-value and the population density. The reproduction number got with w_R= 0,7 the highest weight, the population density received a weight of w_{PD}= 0,3. The R-value received the higher weight, because it is the main indicator of the spread of the coronavirus, giving the number of people that one COVID-19 positive person infects (Annunziato and Asikainen, 2020, p.6). The population density just gives a general impression about the spread of diseases and with that the strength of possibility for a circulation of a virus (Tarwater and Martin, 2001, p. 35). Due to this it gets a lower weight. The following formula was used to get a single scaled threat value (T_{scaled}) for each region:

$$T_{scaled} = R_{scaled} \cdot w_R + PD_{scaled} \cdot w_{PD}$$

Using this calculation, we received a T_{scaled} of 100 for Region West, 77 for Region East and 84 for Region South. As an example, the T_{scaled} = 77 for Region East means that the value of threat is only 77% as high as for Region West. According to Goodwin and Wright, we need to bring the individual values of benefit for each region on one common scale since the before mentioned value of 100 in one region, might not be as preferable as a value of 100 for another region (Goodwin and Wright, 2000, pp. 321-323). For that reason, the longest scale will be the common scale (Goodwin and Wright, 2000, pp. 321-323). Region West has the highest calculated value of threat with 100 and will be used as the common scale. That means, the scales for Region East and South have to be measured on the common scale of Region West. For transforming the values on the common scale of Region West the following calculation was used:

$$T_{common\,scale} = T_{individual} \cdot \frac{T_{scaled}}{100}$$

The $T_{individual}$ of each region and for each strategy was multiplied with the corresponding T_{scaled} of the region and divided by one hundred. This way we can get the corresponding benefit values, according to the threat level, on a common scale reaching from 0-100. The calculated values can be found in the table 10.

Table 10: Threat benefits considering within-criterion weights

	Region West	Region East	Region South
Strategy 1 (10%)	0	0	0
Strategy 2 (20%)	72	56	61
Strategy 3 (30%)	100	77	84

The table depicts that Region West has the highest threat, followed by Region South and last Region East.

6.4. Results

In the preceding sections we calculated the individual benefits for each region and strategy on a common scale. The results are summarized in table 11. The benefits are divided into costs, threats and vulnerability with a subdividing of costs into Transport and warehouse costs and vulnerability into Health System Capacity and hospital and intensive care unit beds.

You can see that in terms of costs, strategy 1 is the best in each region, while threats and vulnerability (HSC and Hospital and intensive care unit beds) recommend strategy 3 for each region with the amount of resources needed increasing from strategy 1 to 3.

Table 11: Values of strategies with each benefit measured on common scale

Regions	Strategies	Vaccine doses (thousands)	Benefits				
			Transport costs	Warehouse costs	Threat	Health System Capacity	Hospital and intensive care unit beds
Region East	Strategy 1	49.444	90,91	92,00	0,00	0,00	0,00
	Strategy 2	98.887	50,00	48,00	72,00	70,00	80,00
	Strategy 3	148.331	0,00	0,00	100,00	100,00	100,00
Region West	Strategy 1	34.079	100,00	96,00	0,00	0,00	0,00
	Strategy 2	68.158	68,18	56,00	55,44	43,42	43,90
	Strategy 3	102.237	27,27	12,00	77,00	72,37	62,71
Region South	Strategy 1	42.753	95,45	100,00	0,00	0,00	0,00
	Strategy 2	85.506	59,09	64,00	60,48	54,71	35,45
	Strategy 3	128.259	13,64	16,00	84,00	91,19	59,08

6.5. Across-criteria weights

According to Goodwin and Wright it is necessary to compare the relative importance of the benefits, meaning the formulation of normalized weights (Goodwin and Wright, 2000, pp. 324-325). This allows us to calculate and assess the general benefit of the combination of different strategies in the shape of packages. With the help of the efficient frontier, we can then exclude packages, which offer less or the same benefit with a higher amount of resources (Goodwin and Wright, 2000, pp. 326-327).

The Assessment of across-criteria weights was accomplished through discussions in the group and based on the prioritization of benefits according to WHO guidelines. Also being in accordance with the general framework of our work, which would be setting a strategic approach to fight the threat of coronavirus in countries mostly affected and help the countries with less developed Health System Capacities, was considered. Another issue was to take the logistics-related difficulties and expenses for delivery to each region into account. From the point of view of this approach and at a general level, we agreed on starting to give each benefit area a weight of 33%. Then we decided to treat threat and vulnerability factors equally and set the goal to reach the equal value for both, i.e., increasing them at the same time and with the same steps towards equal values.

Supporting Health System Capacity and reducing the threats of COVID-19 plays a central role in our proposed goal system and analysis model. Therefore, we gradually increased the values for threat and vulnerability from 33% and finally agreed on 36% for each. By assessing the values for threats and vulnerabilities, the benefit value for costs was automatically calculated, being the percentage left to achieve 100%, a value of 28%

We agreed that the two different cost aspects should have a different weight. Warehousing costs are in our opinion more important than transport costs, because in cases of power shortages the vaccine might lose its effect and therefore become unusable. With a higher weight on warehouse costs, we make sure that this is taken into consideration. Cooling down vaccines in a warm temperature is harder than in a cool temperature and therefore it is more likely that the cooling fails. We agreed on giving Warehouse Costs a weight of 16% and transport costs a weight of 12%. A report of Mvundura et al shows that the warehouse Costs are also higher than the transport costs. This is another evidence that warehouse costs should be valued higher than the transport costs (Mvundura et al., 2014, p.836).

The chosen across-criteria weights are shown in the table 12 on the next page.

Table 12: Across-criteria weights

Transport Cost	Warehouse Cost	Threat	Health System Capacity	Hospital and intensive care unit beds
12,0%	16,0%	36%	18%	18%

6.6. Identifying Costs and benefits of strategic packages

As a result of analysis of resources and benefits as mentioned before, at this stage we can compare the relative values for each strategy. The resources were calculated through the following formula:

$$V_{S_R} = S_R \cdot P_R$$

In which V_{S_R} represents the value of foreseen vaccine doses of each strategy for a given region, while S_R and P_R would respectively represent the due amount of allocation per strategy (%) and population of each region (thousand). One example for Region West using strategy 1 (10%) would be V_{S_R}= 0,1*494.444 = 49.444 thousand doses or 49,444 million doses.

According to Goodwin and Wright it is now possible to assess the benefits of each possible strategy package and depict them in a graph (Goodwin and Wright, 2000, p. 326). Our study has three different regions with three different strategies for each, combining these we receive 3^3 or 27 possible combinations, called packages.

We set the X axis as the amount of doses. The doses were calculated using the formula $x = \sum v_{S_R}$.with v_{S_R}.being the amount of vaccines (v) for the used strategy (s) in the considered region (r).

The Y axis shows the achieved value of benefit when combining certain strategies of the regions West, East and South. For achieving this we first calculated the overall benefit of each strategy in each region using the following formula:

$$B_{R_S} = C_T \cdot w_{C_T} + C_w \cdot w_{C_w} + T_{common\ scale} \cdot w_T + H_C \cdot w_{H_C} + Be_{HI} \cdot w_{B_{HI}}$$

$B_{R_S}$is the Benefit for the used strategy (S) in the Region West, East or South. The value for transport costs (C_T) is multiplied with the across-criteria weight w_{C_T} , the value for warehousing costs (C_w) is multiplied with the matching weight w_{C_w}, the threat value $T_{common\ scale}$ is multiplied with its weight w_T, the benefit value for Health System Capacity H_C is multiplied with the across-criteria weight w_{H_C} and the value for Beds in hospital and intensive care units are multiplied respectively with $w_{B_{HI}}$. For receiving the B_{R_S} it is now necessary to add all the numbers up. Since we have three different regions with three different strategies, we will receive 3x3 or nine different values, shown in table 13.

Table 13: Overall benefit for each strategy

Strategies	Vaccines	Benefit
Region East		
Strategy 1	49.444	26
Strategy 2	98.887	67
Strategy 3	148.331	72
Region West		
Strategy 1	34.079	27
Strategy 2	68.158	53
Strategy 3	102.237	57
Region South		
Strategy 1	42.753	27
Strategy 2	85.506	55
Strategy 3	128.259	61

The next step to receive the overall benefit of the combination of strategies is to take the sum of the single B_{R_S} that are included in the considered package. Again, since we have 27 possible combinations for packages, we will receive 27 not scaled benefit values $B_{not\ scaled}$.

$$B_{not\ scaled} = \sum B_{R_S}$$

Goodwin and Wright suggest the scaling of the benefits on a 0-100 scale with 0 being the worst and 100 being the best package for easier interpretation of the benefits (Goodwin and Wright, 200, p.326). For this we set the lowest $B_{not\ scaled}$ to a value of zero and the highest $B_{not\ scaled}$ to a value of 100. To receive B_{scaled} we used the formula

$$B_{scaled} = \frac{100}{(B_{not\ saled\ max} - B_{not\ scaled\ min})} * \ (B_{not\ scaled} - B_{not\ scaled\ min})$$

This formula depicts that we scaled the range of ($B_{not\ saled\ max} - B_{not\ scaled\ min}$)on a scale of 0-100 and multiplied this with the value of $B_{not\ scaled}$ minus $B_{not\ scaled\ min}$since we set the $B_{not\ scaled\ min}$ value as zero.

The results of the packages, illustrated as x for vaccine doses and y for B_{scaled}, are shown in the following table and graph. The numerical combination that is shown in brackets behind each indicates the set of strategies, with the first number indicating the strategy for Region West, the second number indicating Region East's strategy and the third number region South's strategy. For example, Package 15 consists of Region West - strategy 2, Region East strategy 2 and Region South strategy 3.

Table 14: List of strategic packages and their properties

Package	Vaccine doses (x)	Benefit (y)	Package	Vaccine doses (x)	Benefit (y)
Package 1 (111)	126.276	0	**Package 15 (223)**	295.304	91
Package 2 (112)	169.029	25	**Package 16 (231)**	243.877	64
Package 3 (113)	211.782	31	**Package 17 (232)**	286.630	90
Package 4 (121)	160.354	23	**Package 18 (233)**	329.383	95
Package 5 (122)	203.108	48	**Package 19 (311**	225.163	42
Package 6 (123)	245.861	54	**Package 20 (312)**	267.916	67
Package 7 (131)	194.433	27	**Package 21 (313)**	310.669	73
Package 8 (132)	237.187	52	**Package 22 (321)**	259.242	65
Package 9 (133)	279.940	58	**Package 23 (322)**	301.995	90
Package 10 (211)	175.719	37	**Package 24 (323)**	344.748	96
Package 11 (212)	218.472	62	**Package 25 (331)**	293.321	69

Package	Vaccine doses (x)	Benefit (y)	Package	Vaccine doses (x)	Benefit (y)
Package 12 (213)	261.225	68	**Package 26 (332)**	336.074	94
Package 13 (221)	209.798	60	**Package 27 (333)**	378.827	100
Package 14 (222)	252.551	86			

6.7. Results

The values listed in table 14 can be used as coordinates to give a graphic illustration of strategies from the viewpoint of resources and benefits. The graph illustrating the benefits and amount of doses for each package helps to find the package that offers the highest benefit for a given amount of available resources (Goodwin and Wright, 2000, pp. 326-328). By mapping the strategies in regards to their resource allocation (x axis) and benefits value (Y axis) in figure 4 the efficient frontier for the proposed packages can be realised. Therefore, at each resource level, we chose the strategy with the highest benefit to be positioned on the efficient frontier. Likewise, for each equal benefit level, the strategy with the minimum resource need would be positioned on the efficient frontier. In Figure 4 the efficient frontier links those packages which offer the highest value of benefits for a given resource level (or the lowest resource need for a given level of benefits).

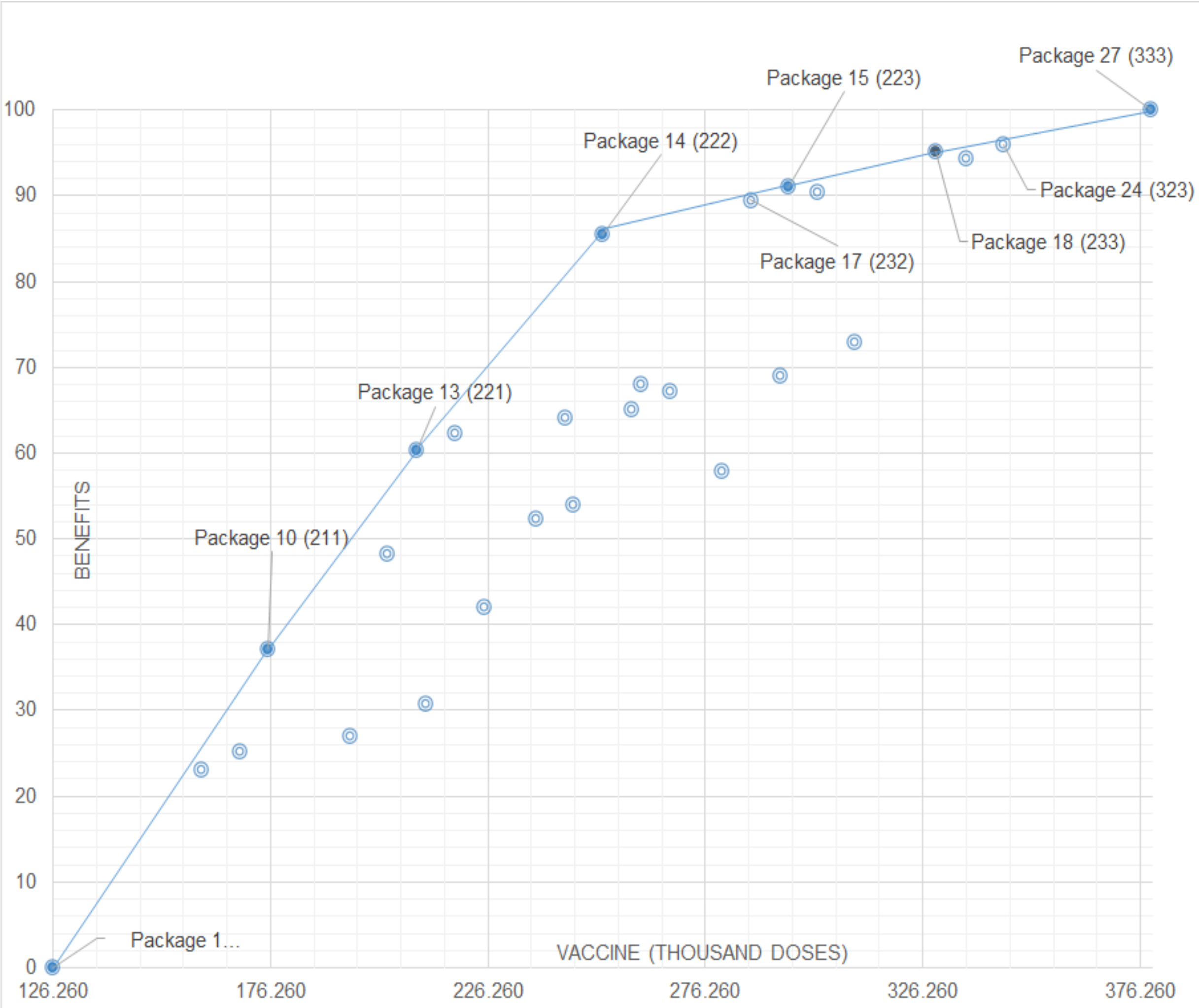

Figure 4: Identification of efficient frontier

As Figure 4 implies, 7 combinations of packages are positioned on the efficient frontier (table 15). As explained before, each package on the efficient frontier is an outcome of constant trade-off between resources and benefits, hence exclusion of other packages. The efficient frontier is a good decision-making tool to observe the most optimal set of strategies for each interval of resources (X axis in figure 4). Therefore, assuming Covax has access to only 126 million doses (as indicated by the weakest set of strategies), the only option would obviously be package 1. While when e.g., access to 200 million doses is facilitated, the necessary precondition would be fulfilled for acquisition of strategy 10 (which requires almost 175 million doses). The same analysis can be applied for other resource access levels.

As figure 4 indicates, the efficient frontier is obviously steeper as we approach package 14 and after that point takes a considerably milder slope towards package 27, suggesting that by increasing the resources to package 14 the benefits relative score is increasing at a higher pace, meaning moving in the relative interval (126-252 million doses) provides stronger increase in benefits. From this point of view package 14 would be seen as the most desired combination of strategies, because at an optimal resource access level, it can yield benefits that are meaningfully higher than all other lower packages (Packages 1, 10 and 13)

In case of access to higher levels of resources we have identified 3 packages as most beneficial (packages 15, 18 and 27), while packages 17 and 24 are also appropriate in terms of resource-benefit ratio, that they provide. However, these packages are visibly not positioned on the efficient frontier and therefore put aside from acceptable strategic packages.

Table 15: Selected strategic packages

Strategies packages	Resource necessity (thousand doses)	Benefits score
Package 1 (111)	126.276	0
Package 10 (211)	175.719	37
Package 13 (221)	209.798	60
Package 14 (222)	**252.551**	**86**
Package 15 (223)	295.304	91
Package 18 (233)	329.383	95
Package 27 (333)	378.827	100

Assuming that we are able to provide between 250 and 260 million doses until summer, we can read from the graph that the package with the highest benefit is package 14. It is the one which is lying on the efficient frontier. Package 14 consists of 252.551 thousand doses and has a benefit score of B_{scaled} = 86. This means that it is 86% better in benefits compared to the worst package, number 1. If we could not guarantee to produce more than 250 million doses, our next package lying on the efficient frontier was package 13, consisting of 209.798 thousand doses and a B_{scaled} of 60. We as decision makers decided that it would be better to go for package 14 since it offers a 26% better package in benefits with just a 20% increase in doses compared to package 13. That means that the increase in benefits is higher than the increase in needed vaccines. For that reason, we suggest that the production should aim for 252.551 thousand doses to achieve the best possible outcome. Modifications in the production line, extending working hours or shortening maintenance periods might be possible variables for ensuring the distribution of the given amount of resources and achievement of the best possible outcome.

7. Conclusion

7.1. Summary

The goal of this term paper was to find the best way to distribute vaccines, from the point of view of the Covax approach, for each quantity of vaccines produced. The decision analysis method we therefore used was the Resource Allocation Model.

For this purpose, we approached the problem with the following steps. First, we selected the benefits and variables needed to apply for the Resource Allocation Model. We then created strategies to be able to calculate combinations of vaccine allocation, from which strategic packages were built. We furthermore evaluated the performance of each type of benefit for all three regions (table 7). Later on, we measured them on a common scale for each benefit, region and strategy. As to identify the common scale we assigned the within criterion weights for each benefit (table 11). Then we compared each type of benefit and assigned their relative priority by using across-criteria weights. (table 12)

Moreover, we were able to assess the overall benefit for a combination of strategies in the regions through across-criteria weighting. The calculated overall benefit of the packages allowed us to map the benefit in comparison to the vaccine dose for the 27 possible strategies in a graph and determine an efficient frontier (see figure 4). Through this efficient frontier we were able to find the best possible package for a given amount of resources, in our case vaccine doses. As an example, we could determine that package 14 is the best possible outcome for an available amount of 250 to 260 million doses for distribution. Package 14 consists of strategy 2 for Region West, East and South, meaning that all regions should receive an amount of vaccine doses that represent 20% of the population.

As a result of analysis of the gathered information we could create a graph showing each package with the amount of needed Resource and the amount of relative benefit (Figure 4). As a result, we have access to a tool to distinguish the best strategies (with highest benefits) for any given input of resources (Vaccine doses).

The importance of such a model in the toolbox of decision making parties is not needed to be emphasized. At these times when Pandemic is taking toll on lives and also damaging economies worldwide, the decision making organizations at both national and international level have to react as fast and efficiently as possible to the pandemic despite the burden of resources scarcity.

7.2. Limitations

Goodwin's sensitivity analysis in the Resource Allocation Method relies mainly on changing the costs or in our case the needed resources. We have already explained the efficient frontier and points which are close to the efficient frontier and therefore approached the sensitivity analysis. If it comes to the across-criteria, it should be mentioned, that if we reduce the weight for the costs (transport costs and/ or warehouse costs) then the correlation between the needed resources and the benefits would be rising. This means that the packages are getting closer to each other. Furthermore, Goodwin mentions different resource inputs in his sensitivity analysis, which therefore doesn't concern our case (Goodwin and Wright, 2004, pp. 343, 344).

In addition, it is important to state that our results are based on approaches we discussed as a group of decision makers. Accordingly, the results could change if another group of decision makers would apply the Resource Allocation Method for the distribution or rather allocation of vaccines to regions in Africa. First, the across criteria and/ or the benefits could be set and calculated differently. They could also take different criteria into consideration. We have also created our own strategy, for example the COVAX strategy, which we set differently. Besides we assumed that only one vaccine dose is necessary, whereas in reality some vaccines need to be injected twice (CDC, 2020). Apart from that the Corona Mutations reported in the media, could influence the distribution of vaccines (Lone and Ahmad, 2020, p.1301). Also due to lack of data we excluded the circulation of influenza viruses as a variable for threat and used population density, a general indicator for the spread of diseases, instead. Since the WHO suggests to use the presence of influenza viruses as a variable for threat, it could be considered in future models if data becomes available (WHO, 2020, p. 27). Furthermore, the received reproduction values need to be looked at in more detail. There might be an influence and falsifying of data due to one region testing more than the other or people not going to the doctor since not all people in Africa have health insurance (Appiah, 2012, p.125-126).

Last but not least, factors like the political stability and other macro environmental factors (i.e., piracy) weren't taken into consideration.

Annexes

Annex 1: Vulnerability value for African countries (Regions)

Regions	Country	Vulnerability			
		HSC for Regions	Health system capacity (HSC) indicator	Hospital and intensive care unit bed for Regions	Occupancy of hospital and intensive care unit beds
West	Cape Verde	0,022	0,014	0,035	0,010
	Morocco		0,014		0,016
	Mauritiana		0,024		0,045
	Senegal		0,022		0,059
	Benin		0,025		0,036
	Ghana		0,021		0,020
	Tunisia		0,014		0,010
	Cote divoire		0,021		0,045
	Niger		0,027		0,045
	Nigeria		0,024		0,036
	Gambia		0,023		0,016
	Burkina Faso		0,025		0,045
	Guinea-Bissau		0,025		0,018
	Liberia		0,026		0,023
	Mali		0,026		0,077
	Guinea		0,027		0,059
	Sierra Leone		0,026		0,045
	Togo		0,023		0,026
	Algeria		0,013		0,010
East	Egypt	0,023	0,015	0,032	0,013
	Sudan		0,023		0,027
	South Sudan		0,032		0,021
	Chad		0,036		0,045
	Cameroon		0,022		0,014
	Sao Tome		0,018		0,010
	Central African Republic		0,030		0,018
	Djibouti		0,021		0,013
	Ethiopia		0,026		0,056
	Somalia		0,040		0,021
	Eritrea		0,026		0,026
South	DR Congo	0,023	0,026	0,024	0,011
	Rwanda		0,018		0,011
	Uganda		0,022		0,036
	Mozambique		0,022		0,026
	Burundi		0,024		0,023
	Madagascar		0,036		0,091
	Malawi		0,022		0,014
	Congo Republic		0,024		0,023
	Kenya		0,018		0,013
	Tanzania		0,023		0,026
	Zimbabwe		0,019		0,011
	Angola		0,025		0,023
	Zambia		0,019		0,010
	Lesotho		0,016		0,010
	Eswatini		0,016		0,010
	Comoros		0,019		0,010

Annex 2: R- and PD-values value for African countries (Regions)

	R-country	R-weighted	R-average	R-scaled	PD	PD-weighted	PD-average	PD-scaled
Cape Verde	1,02	0,00			138	0,16		
Morocco	0,86	0,06			83	6,20		
Mauritiana	1,38	0,01			5	0,05		
Senegal	1,45	0,05			87	2,95		
Benin	0,84	0,02			108	2,65		
Ghana	1,16	0,07			137	8,61		
Tunisia	1,10	0,03			76	1,82		
Cote divoire	1,24	0,07			83	4,43		
Niger	1,31	0,06			19	0,93		
Nigeria	1,37	0,57	1,19	100,00	226	94,22	135,24	100,00
Gambia	0,66	0,00			239	1,17		
Burkina Faso	1,24	0,05			76	3,21		
Guinea-Bissau	0,16	0,00			70	0,28		
Liberia	0,31	0,00			53	0,54		
Mali	1,09	0,04			17	0,70		
Guinea	1,04	0,03			53	1,41		
Sierra Leone	1,17	0,02			111	1,79		
Togo	1,07	0,02			152	2,55		
Algeria	0,78	0,07			18	1,60		
Egypt	1,20	0,36			103	30,93		
Sudan	0,94	0,12			25	3,22		
South Sudan	0,89	0,03			18	0,59		
Chad	1,22	0,06			13	0,63		
Cameroon	0,87	0,07			56	4,36		
Sao Tome	0,70	0,00	1,01	84,93	228	0,15	80,44	59,48
Central African Republic	0,36	0,01			8	0,11		
Djibouti	1,21	0,00			43	0,12		
Ethiopia	0,96	0,32			115	38,79		
Somalia	0,52	0,02			25	1,17		
Eritrea	1,11	0,01			35	0,36		
DR Congo	1,15	0,28			40	8,38		
Rwanda	1,30	0,05			525	15,91		
Uganda	1,13	0,14			229	24,50		
Mozambique	1,13	0,10			40	2,92		
Burundi	1,02	0,03			463	12,88		
Madagascar	0,31	0,02			48	3,11		
Malawi	1,57	0,08			203	9,08		
Congo Republic	0,52	0,01	1,04	87,61	16	0,21	104,05	76,94
Kenya	0,76	0,11			94	11,82		
Tanzania	0,00	0,00			67	9,36		
Zimbabwe	1,30	0,05			38	1,32		
Angola	1,02	0,09			26	2,00		
Zambia	1,24	0,06			25	1,08		
Lesotho	1,23	0,01			71	0,36		
Comoros	0,75	0,00			467	0,95		
Eswatini	1,46	0,00			67	0,18		

Annex 3: Transport Index and Average Temperature

Region	Country	Population in 1000	Average Road	Average Railroad	Average Port	Average Airport	Transport Index	Average Temperature [E]
West	Algeria	43.851,00	3,75[C]	3,6[C]	3,65[C]	3,85[C]	3,785	22,5
	Benin	12.123,00	3,05[C]	1,55[C]	3,8[C]	3,65[C]	3,335	27,55
	Burkina Faso	20.903,00	2,8[A]	2,5[A]	2,8[A]	3,4[A]	3,13	28,25
	Cape Verde	556,00	3,95[C]	1[D]	3,4[C]	3,6[C]	3,39	23,3
	Cote divoire	26.378,00	3,6[A]	2,9[A]	4[A]	4,6[A]	4,17	26,35
	Gambia	2.417,00	3,9[C]	1[D]	4,15[C]	4,45[C]	3,965	27,5
	Ghana	31.073,00	3,45[C]	1,85[C]	3,35[C]	3,8[C]	3,49	27,2
	Guinea	13.133,00	2,95[C]	2,2[D]	4,2[C]	4,25[C]	3,78	25,7
	Guinea-Bissau	1.968,00	2,1[D]	1[D]	3,9[D]	1,4[D]	1,75	26,75
	Liberia	5.058,00	3[B]	1,4[D]	3,2[B]	2,8[B]	2,74	25,3
	Mali	20.251,00	3,4[C]	2,1[B]	2,05[C]	4[C]	3,495	28,25
	Mauritania	4.650,00	2[C]	2,15[C]	2,3[A]	2,4[C]	2,285	27,65
	Morocco	36.911,00	4,6[C]	3,9[C]	5,05[C]	5,05[C]	4,845	17,1
	Niger	24.207,00	2,2[D]	1,2[D]	1,7[D]	2[D]	1,93	27,15
	Nigeria	206.140,00	2,5[C]	1,65[C]	2,65[C]	3,15[C]	2,82	26,8
	Senegal	16.744,00	3,9[C]	2,55[C]	4,2[C]	4,35[C]	4,065	27,85
	Sierra Leone	7.977,00	3,2[B]	1[D]	3,3[B]	2,8[B]	2,75	26,05
	Togo	8.279,00	2,5[D]	1,1[D]	3,2[D]	1,8[D]	2,01	27,15
	Tunisia	11.819,00	3,65[C]	3[C]	3,35[C]	3,75[C]	3,615	19,2
East	Cameroon	26.546,00	2,5[C]	2,5[C]	3,1[C]	3,05[C]	2,89	24,6
	Central African Republic	4.830,00	1,4[D]	1[D]	1,5[D]	2,8[D]	2,21	24,9
	Chad	16.426,00	2,25[C]	1[D]	1,95[C]	2,9[C]	2,485	26,55
	Djibouti	988,00	3[D]	1,5[D]	3,8[D]	2,3[D]	2,51	28
	Egypt	102.334,00	4,5[C]	3,55[C]	4,75[C]	5,1[C]	4,79	22,1
	Eritrea	3.546,00	3,3[D]	1,2[D]	1,8[D]	2,5[D]	2,46	25,5
	Ethiopia	114.964,00	3,15[C]	2,95[C]	2,75[C]	3,75[C]	3,45	22,2
	Sao Tome	219,00	3,9[D]	1[D]	3[D]	2[D]	2,38	23,75

Region	Country	Population in 1000	Average Road	Average Railroad	Average Port	Average Airport	Transport Index	Average Temperature [E]
	Somalia	15.893,00	2,3[D]	1,1[D]	2,6[D]	2,8[D]	2,51	27,05
	South Sudan	11.194,00	2,3[D]	1,1[D]	1[D]	1,5[D]	1,57	26,9
	Sudan	43.849,00	2,5[D]	2,3[D]	2,7[D]	1,7[D]	2,02	26,9
South	Angola	32.866,00	2,2[A]	2,5[D]	2,8[A]	3,3[A]	2,95	21,55
	Burundi	11.891,00	3,45[C]	1[D]	3[C]	3,4[C]	3,13	19,8
	Comoros	870,00	2,3[D]	1[D]	3,5[D]	3[D]	2,71	25,55
	Congo Republic	5.518,00	3,2[D]	1,4[D]	3,2[D]	2,7[D]	2,72	24,55
	DR Congo	89.561,00	2,1[C]	1,9[C]	2,55[C]	2,9[C]	2,605	24
	Eswatini	1.160,00	4,35[C]	3,5[B]	3,5[C]	3,95[C]	3,94	17,75
	Kenya	53.771,00	4,2[C]	4[A]	4,35[C]	4,95[C]	4,645	24,75
	Lesotho	2.142,00	2,65[C]	1[D]	3[B]	1,25[C]	1,68	11,85
	Madagascar	27.691,00	2,1[C]	1,95[C]	3,5[C]	3,5[C]	3,065	22,65
	Malawi	19.130,00	2,8[C]	2,1[C]	2,15[C]	2,85[C]	2,695	21,9
	Mozambique	31.255,00	2,45[C]	2,55[C]	3,45[C]	3,25[C]	3,04	23,8
	Rwanda	12.952,00	4,9[C]	1[D]	3,05[C]	4,85[C]	4,295	17,85
	Tanzania	59.734,00	3,8[C]	3[C]	3,75[C]	3,75[C]	3,685	22,35
	Uganda	45.741,00	3,55[C]	1,6[B]	2,65[C]	3,35[C]	3,145	22,8
	Zambia	18.384,00	3,5[C]	2,25[C]	2,5[C]	3,65[C]	3,365	21,4
	Zimbabwe	14.863,00	2,8[C]	2[C]	3,1[C]	3,6[C]	3,23	21

Cells Marked with [A] have the source from the Global Economy
Cells Marked with [B] have the source from WorldEconomyForum
Cells Marked with [C] have the source from [A] and [B]
Cells Marked with [D] have the sources shown in Exhibit XY
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