Mathematical Model to Explain the Spread Performance of the Coronavirus (COVID-19) in Peru

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ABSTRACT

In Peru there have been many policies and actions that did not lead to effective solutions regarding COVID-19. One cause of this is the ignorance of the main variables and factors that influence its performance. Consequently, the number of active cases increases as well as the number of deaths.

Therefore, this research proposes the development of a model for the analysis of the performance of COVID-19 in Peru. Based on the SIR-D epidemiological model, a simulation was carried out applying concepts and system dynamics tools to determine the main causes and consequences that determine the performance of COVID-19 from March 31 to December 16, 2020.

This work evidenced the main socioeconomic factors that influenced the performance of COVID-19: informality, precarious infrastructure of water and sewerage services, lack of public awareness, among others.

Keywords: COVID-19 in Peru, System Dynamics, performance of COVID-19, critical factors.

INTRODUCTION

The first case of coronavirus in the world occurred in a 55-year-old person in the Hubei province, Wuhan, confirmed on November 17, 2019 (Diario Libre, 2020). Subsequently, on December 31 of the same year, the Wuhan Municipal Health Commission determined that the clusters of pneumonia cases in the city were caused by the new coronavirus (WHO, 2020a). Due to the rapid spread of the virus, countries such as China, Thailand, France, and much of Europe were already infected within a month of the first outbreak of the disease.

The scenario that we are currently going through in Peru began when case zero arrived in Lima. Former President Vizcarra confirmed on March 6, 2020, that a 25-year-old man who made a trip to Spain, France and the Czech Republic, was the first infected with COVID-19 in the country (Lira, July, 2020). On March 11, 2020, the WHO declared the new coronavirus a pandemic and urged countries to take a whole-of-government and a whole-of-society approach, around a comprehensive strategy aimed at preventing infections, saving lives, and minimizing the consequences of the pandemic (WHO, 2020b). For that reason, then President Martín Vizcarra announced the issuance of an emergency decree imposing a general lockdown for 15 days starting on March 16, within the framework of a Declaration of a State of National Emergency (Gestion, 2020). This decision has been in force for 347 days until February 26 of this year. But, due to the advance of COVID-19 in Peru, the Executive Power decided to extend the state of health emergency, nationwide, until September 2, 2021, through Supreme Decree 009-2021-SA (Redacción EC, 2021).

Throughout the mandatory quarantine, measures were taken against the spread of the virus in the country. However, Peru was identified as the country that handle coronavirus the worst (Redacción EC, 2020). As a result, Peru became the country with the highest mortality in the world due to COVID-19 in August 2020, with more than 28,000 coronavirus deaths in the country, resulting a mortality of 85.8 deaths for each 100,000 inhabitants (Valero, 2020).

In the midst of the COVID-19 crisis, the rulers' lack of knowledge about the main variables that play out in the performance of the virus in the short and medium term had to be dealt with. Since the measures taken did not make it possible to deal with the economic and health crisis in the country. In that sense, despite the government's efforts to provide a solution, none of these measures was the most adequate response to mitigate the causes of COVID-19 expansion.

For example, the "Peak and gender" measure, which restricted the movement of people according to their gender on different days of the week, was eliminated after 8 days, as it did not meet the objective of reducing the number of contacts (Reisman, 2020). In addition, social measures to support the most vulnerable families, such as the vouchers provided by the government, led to the formation of crowds in the banks and, consequently, a contravention of the public health measures ordered by the government itself (Mundo, 2020a). On the other hand, budget execution was focused more on implementing hospitals with ICU areas. Investing in rapid tests instead of molecular tests was another mistake that enabled a rapid increase in the Covid-19 contagion rate. The resources directed to awareness activities, diagnostic capacity and isolation policies were not sufficiently effective. In general, it can be said that the government had a more hospital-centric approach than a preventive and infected detection, that is, a reactive policy instead of a preventive one (Mundo, 2020b).

In the literature, the current problems facing the world (such as immigration, misuse of natural resources, poverty, Covid-19, etc.) are highly complex, and System Dynamics is a method that allows us to generate a perspective closer to reality by contemplating causal relationships between concepts. System dynamics as a method allows to analyze systems and simulate past and future behaviors (Vicente, 1989). This method also allows us to construct a formal object, which will be a dynamic system in the mathematical sense of the term, and consequently we obtain a model of that aspect of the reality we are trying to study (Aracil Javier, 2007). The model will also be used to perform different simulations and to study the consequences of the multiple interactions of the elements or variables of the system over time.

The application domain of system dynamics is wide and there are different proposals applied to the Covid-19 problem. Among them, according to our context, we highlight the following: Pino et al (Pino, Quispe, & Soto-Becerra, 2020), published the article "A Segmented SIR-D Mathematical Model for the Propagation Dynamics of the Coronavirus (COVID-19) in Peru". This article presents information that is often key to guide decision-making in the fight against epidemics, where it proposes the use of a segmented SIR-D mathematical model to predict the evolution of epidemiological populations of interest in the COVID-19 pandemic The article performs the segmentation of the model in 6 stages of periods of 14 days each one, which allowed to know during the fortnightly time how the epidemiological rates evolved, and thus, to know the impact of the interventions to reduce contagion. In this case, the article is very interesting for the present work, since it is directly related to the Peruvian situation and system dynamics.

Likewise, Cárdenas et al (Cárdenas Bohórquez, S., and others, 2020), published the article “System Dynamics Model for the Progress of Sars-Cov-2 (COVID-19) in Colombia”. This article exposes the application of system dynamics concepts for the analysis of the progress of SARS-

Cov-2 (COVID 19) using Vensim software application. For the development, the recorded data of the process and the spread of COVID-19 in Colombia were taken into account through the platforms that allow obtaining data such as the daily increase in cases, number of deceased people, etc. As a result, it is evident that the infected population will continue in a constant increase if the pandemic is not controlled or a disease cure is not presented. The positive of this situation is that the cured population presents a greater increase than the sick population; This has been registered in most countries and, therefore, it is feasible to think of a contagion control model. This article is clearly related by its application of tools such as system dynamics, Vensim software and its analysis of the progress of COVID-19.

However, although many studies have achieved outstanding results, it is still very valuable to generate more precise models that allow us to discover the main factors that explain the behavior of Covid-19 in our country, in order to avoid failures in the design of strategies and achieve more effective results.

The objective of this research is to expand the knowledge about the behavior of COVID-19 in Peruvian society. Therefore, we will evaluate the hypothesis: The application of System Dynamics will allow us to analyze and discover the variables that determine the main factors that explain the behavior of the spread of the coronavirus (COVID-19) in Peru.

This document is divided into the following parts: first, the explanation of the methodology and the construction of the model; second, the analysis of the results through assumed scenarios and modification of parameters; and finally, the conclusions are presented.

METHODOLOGY

The present investigation is divided into five phases (Figure 1). In the first phase, we identify and structure the problem: the coronavirus pandemic in Peru. We use the systemic approach to have a broad perspective of the complexity of the problem in the context of the Peruvian reality. According to the father of general systems theory (Bertalanffy, 1987) the holistic vision of the systems approach addresses the problem as a whole, not only analyzing its parts. Under this approach, in addition to the health point of view, other perspectives were explored and analyzed, identifying behaviors from the social and economic point of view.

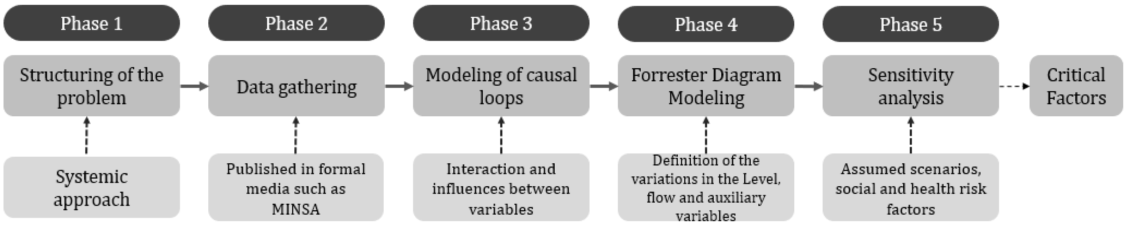
Then, in the second phase, we collected data through the official platforms of the spread of COVID-19 in Peru, such as MINSA. These allowed to know exact data such as the arrival of the first infected person in the country, the number of inhabitants in Peru, the initial infected, the lethality of the disease, the R0 factor, etc. In addition, proposed models and related parameters were taken as reference in previous studies, already explained in the background section.

Then, in the third phase, the modeling of causal ties between the variables was developed and we identified the type of influence (positive or negative), the interaction and feedback between variables.

In the fourth phase, we develop the dynamic model using a Forrester diagram (Jay Forrester) as an instrument. We determined the variables that have a direct and indirect relationship with the problem, the equations were formulated, and the Vensim computer program was used to run the simulations that would explain the behavior of the system under study.

In the fifth and final phase, we perform a sensitivity analysis to examine the results, within which we develop various assumed scenarios. The graphs of the curves correspond to variations in different variables of the model. In this way, we detected key factors in the development of the virus, with which we were able to evaluate strategies and get closer to a greater understanding of reality. However, although we can never exhaust a certain aspect of reality with its representation through a model, certain conclusions were reached that explain the behavior of COVID-19 in our country in the defined period.

Figure 1. Diagram of the methodology



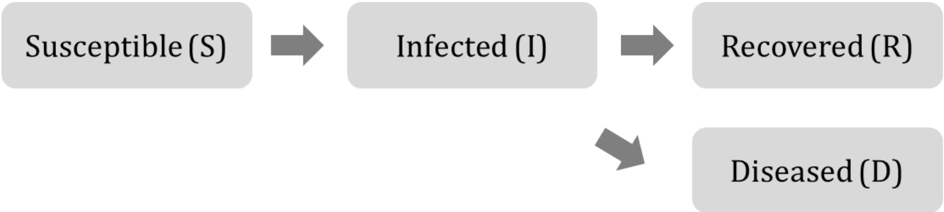
MODEL

The mathematical model focuses on the behavior of COVID-19 considering the characteristics of the Peruvian population and the political actions applied. The core of the model is based on an SIR-D structure (Figure 2) of the article "Estimating and Simulating a SIRD Model of COVID-19 for Many Countries, States and Cities" (Fernández-Villaverde & Jones, 2020), which modifies Kermack-McKendric's SIR model (1927) by applying it to COVID-19.

The present model, based on the SIR-D structure, adds a series of level variables; In addition, exogenous variables related to social risk, political actions to respond to the virus and hospital investment are considered, which have been initialized based on the researched literature. Also, we find endogenous variables in the model whose behavior depends on the influence of variables that are updated by the internal dynamics of the model structure. Among them we have lethality, which depends both on investment in hospital system and on hospital tension, and this in turn on the initial hospital capacity and the hospitalized population.

Based on the structure of this model, the equations have been designed that will allow obtaining the measures of the indicators defined for the model. The simulations under certain parameters will allow knowing the behavior of the impact of the virus, through indicators such as the number of infected, the number of deaths, the number of hospitalized in the defined period.

Figure 2. SIR-D model



The diagram presented in Figure 2 shows the epidemiological populations studied in an SIR-D model: Susceptible (S), Infected (I), Recovered (R) and Deceased (D). However, given the complex study required to deeply analyze a new virus for society, especially its development and development in one of the countries hardest hit by the pandemic, Peru, we have added new level variables. In Appendix A, the variables that make up our mathematical model have been organized into level, flow and auxiliary variables.

Transmission rate (Tt)

In the first segment of the model (*Figure 3*), the infected population (*C*) inoculates the susceptible population (S) with the virus through a transmission rate. On the other hand, we observe that social factors in the demographic space influence the infection flow variable (*I*) and this, in turn, decreases the number of people susceptible to the virus. In addition, the transmission rate variable (*Tt*) is affected by three variables: susceptible fraction (*Fs*), policy actions to combat the virus (*Ap*) and the initial uncontrolled transmission rate (*Ti*). The variable *Ap* is made up of the variables infection confirmation (*Ci*), immediate use of masks (*im*) and reaction time to the disease (*Tre*). These variables involve the government policies adopted by the government, including the measure of strict quarantine. On the other hand, the initial uncontrolled transmission rate depends on the peak of the disease (*Epico*) and R0. The formulas for the above variables are as follows:

$$I = (C * Tt * S)/PT \;) \qquad \text{persons/day} \qquad (1)$$

Where *I* is a fraction of the total *PT* population that becomes infected in one day. It results from the contagion generated by the interaction of the susceptible population *S* with the infected population *C* determined by the transmission rate of the *Tt* virus.

$$Tt = \mathrm{Fs} * \mathrm{Ap} * \mathrm{Ti} \qquad dmnl \qquad (2)$$

Where *Tt* is the probability of spread of Covid-19 on the day. Estimated by the product of a fraction of the population that is prone to infection *Fs* by the indicator *Ap* that expresses the effectiveness of the mitigation measures imposed by the government and *Ti*, a fraction that represents the uncontrolled transmission of the virus despite the preventive measures such as social distancing and hand washing

$$Ap = \mathrm{SMOOTH3}\ (1 - \mathrm{STEP}\ (\mathrm{im}, \mathrm{Ci}), \mathrm{Tre}) \qquad \text{persons/day} \qquad (3)$$

Where *Ap* represents the effectiveness of the containment measures given by the government to control the spread of the disease. The estimate was obtained through the SMOOTH3 function that moderates with a third-order exponential, the input considering a delay time *Tre*, which is the government's reaction time to implement the total quarantine (10 days). The entry (1-STEP (im, Ci)) corresponds to the increase or improvement of *im* given by the use of masks from the *Ci* period, which is day 10 when the first case of Covid-19 was reported in Peru

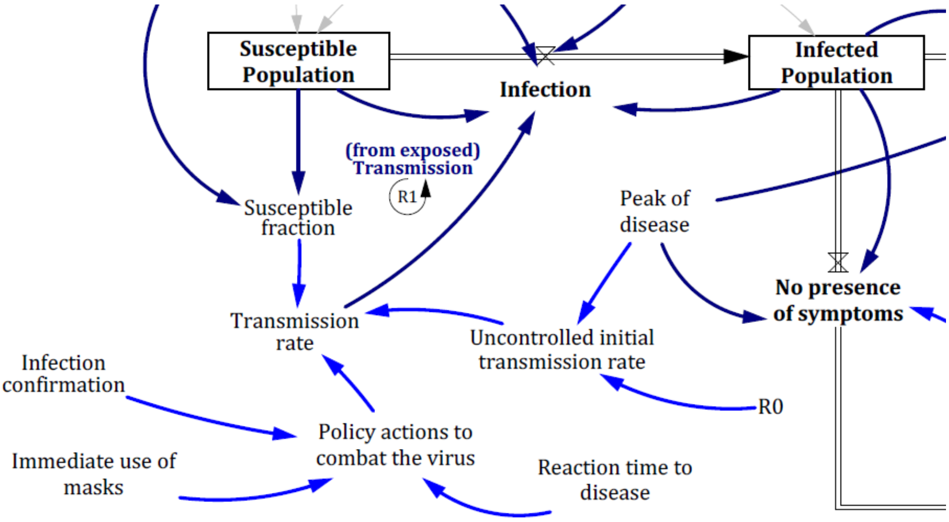
$$Ti = \frac{R0}{E_{pico}} \qquad dmnl \qquad (4)$$

Where *RO* is the expected number of infections caused by an infected individual in the peak period of the disease represented by *Epico* = 7 days.

$$Fs = \frac{S}{PT} \qquad dmnl \qquad (5)$$

Where *Fs* is a fraction of the total population *PT* defined by the amount of population susceptible to contracting the disease.

Figure 3. Virus transmission structure (simplified representation)



Note: Parameters that influence the variable policy actions to combat the virus.

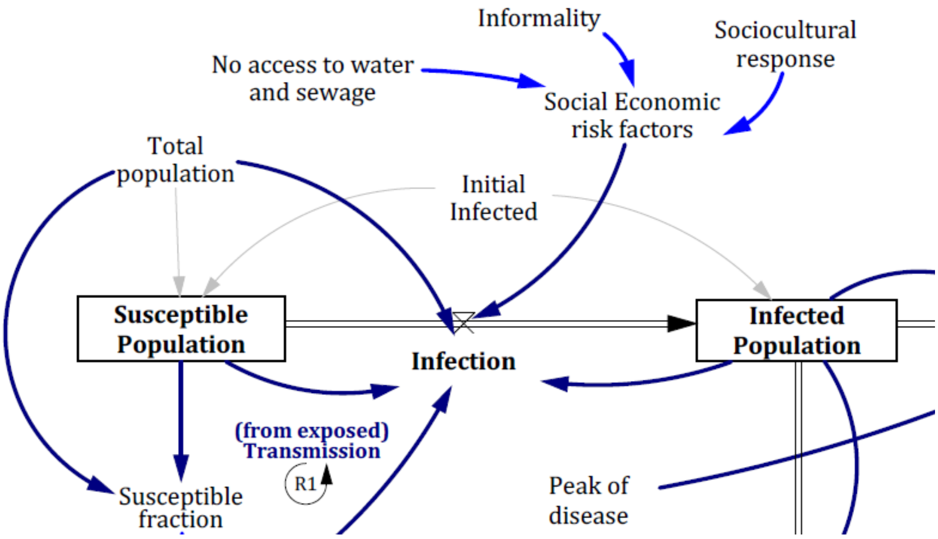
Social Factors

The variable Infection (*I*) depends not only on virus transmission but also on social risk factors (*Fr*) such as informality (*If*) with a value of 0.885, sociocultural response (*Rs*) with a value of 0.9 and no access to water and sewerage (*Sa*) with a value of 0.357. The social factors variable is given by the following formula:

$$Fr = \frac{If + Rs + Sa}{3} \qquad dmnl \qquad (6)$$

Then, as we can see in *Figure 4*, the infected population depends on the number of infected, which is affected by the endogenous variable, social risk factors. In other words, the *Fr* directly influence and have a positive association with the infection variable because if informality increases, the infection variable will increase and, in turn, the number of infected. On the other hand, if *Fr* decreases, the number of infected persons will decrease.

Figure 4. Structure of the infected population (simplified representation)



Note: Parameters that influence the variable Social economic risk factors.

Health sector

The pandemic has stripped the health system bare, therefore one of the factors that mainly influences lethality (*Lt*) is the investment in the hospital system (*Is = 0.089*) focused on the area of COVID-19. In addition, there is another variable that influences lethality, that is, hospital tension (*Th*) which depends on the initial hospital capacity (*CH*) and the number of hospitalized (*H*). As we know, at the beginning of the pandemic our country had only 100 ICU beds dedicated to covid patients at the national level compared to the current total of 12,000; that is, at the beginning there was only 4% availability of intensive care beds for covid patients. Therefore, it was not possible to attend to the people who needed it, causing more contagions and deaths. The formulas for the variables mentioned are as follows:

$$Lt = \frac{0.0379}{0.1 + Th^{Is}} \qquad dmnl \qquad (7)$$

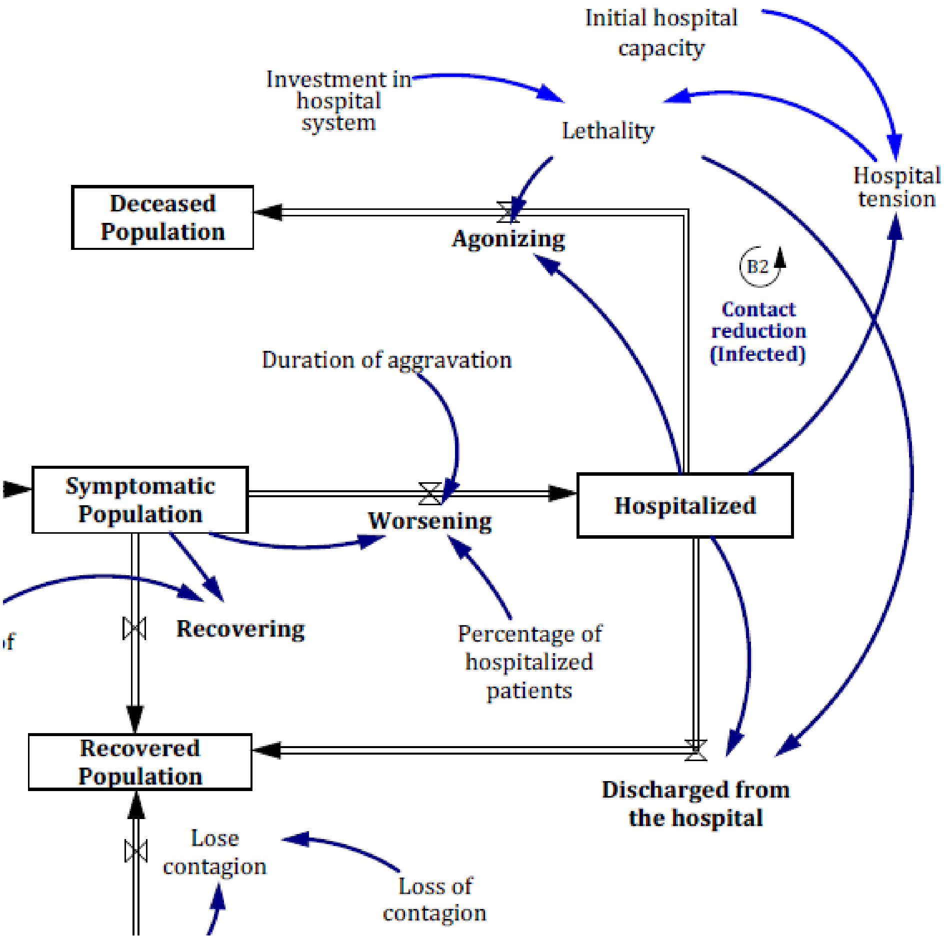
Where *Lt* represents the estimated lethality based on the proportion of people who die from Covid-19 in an infected population in a given period, a value of 0.0379 is considered according to information sources, between an adjustment that includes a constant 0.1 and the tension hospital *Th* raised to an investment factor in the hospital system *Is* that corresponds to 8.9%.

$$Th = \frac{Ch}{H} \qquad dmnl \qquad (8)$$

Where *Th* is the hospital tension that results from the relationship between the initial hospital capacity *Ch* and the number of hospitalized *H.*

Thus, in *Figure 5*, both hospital tension and investment in the hospital system have an influence on the increase or decrease in the number of deaths.

Figure 5. Structure of the recovered, hospitalized and deceased population (simplified representation)



Note: Parameters that influence the variable Lethality and discharged from the hospital.

Mathematical Model for the Development of COVID-19 in Peru

Once the Forrester diagram has been constructed (*Figure 6*), we visualize the interaction of each of the elements of the system and identify each of the variables that represent an accumulation (level variable) or a rate of change (flow variable). The evolution of the level variables turns out to be very significant for the study of the system, since their behavior will allow the simulation to be consistent with reality. For this reason, in this section, the variation of the level variables in our model is based on.

We will start with the **Susceptible Population (*S*)** who are exposed during the contagious period. It is possible that an individual from this population may or may not contract the disease. For this reason, it will depend on the infection variable.

$$S'(t) = -I \qquad persons \tag{9}$$

The greater the number of infected persons, the greater the number of the infected population. However, those infected may present some of the symptoms of the disease or be asymptomatic.

Therefore, the **Infected Population (*C*)** is affected by 4 variables: initial infected (*ii*), infection (*I*), individuals without symptoms (*SS*) and with symptoms (*CS*).

$$C'(t) = I - (SS + CS + ii) \qquad persons \tag{10}$$

$$SS = (C * Pas)/Epico \qquad persons/day \tag{11}$$

$$CS = (C * Ps)/Epico \qquad persons/day \tag{12}$$

As mentioned, many people go through the infection without symptoms or with irrelevant discomfort. On the other hand, the symptomatic group lives with a higher risk of becoming seriously ill and dying. In this case the picture may worsen if they are patients with pre-existing diseases or a weak immune system. Therefore, the level variable **Symptomatic Population (*SI*)** is affected by the outflow variable worsening (*AG*). Another relationship is the outflow variable recovering (*RE*) which is affected by accumulating the number of people recovered from this virus.

$$SI'(t) = CS - (AG + RE) \qquad persons \tag{13}$$

$$AG = (SI * 1 - STEP(Ph, 15))/Da \qquad persons/day \tag{14}$$

$$RE = SI * Pr \qquad persons/day \tag{15}$$

If a patient diagnosed with coronavirus presents signs and symptoms compatible with sepsis (generalized infection) and acute respiratory failure, hospitalization is essential. Consequently, the level variable **Hospitalized (*H*)** will be influenced by the severe cases or the worsening variable (*AG*). In addition, it affects two output variables: cases discharged (*DA*) and agonizing (*AA*). In this case, it will depend on the severity of the disease, and the medical care received.

$$H'(t) = AG - (AA + DA) \qquad persons \tag{16}$$

$$DA = H * (1 - Lt) \qquad persons/day \tag{17}$$

$$AA = H * STEP((1 - Lt), 1) \qquad persons/day \tag{18}$$

On the other hand, **Asymptomatic Population (*AS*)** will be directly influenced by people without symptoms (*SS*). In addition, it positively affects the outflow variable Loss of Contagion (*PC*) since people no longer have the virus in their body and begin to recover.

$$AS'(t) = SS - PC \qquad persons \tag{19}$$

$$PC = AS/PerC \qquad persons/day \tag{20}$$

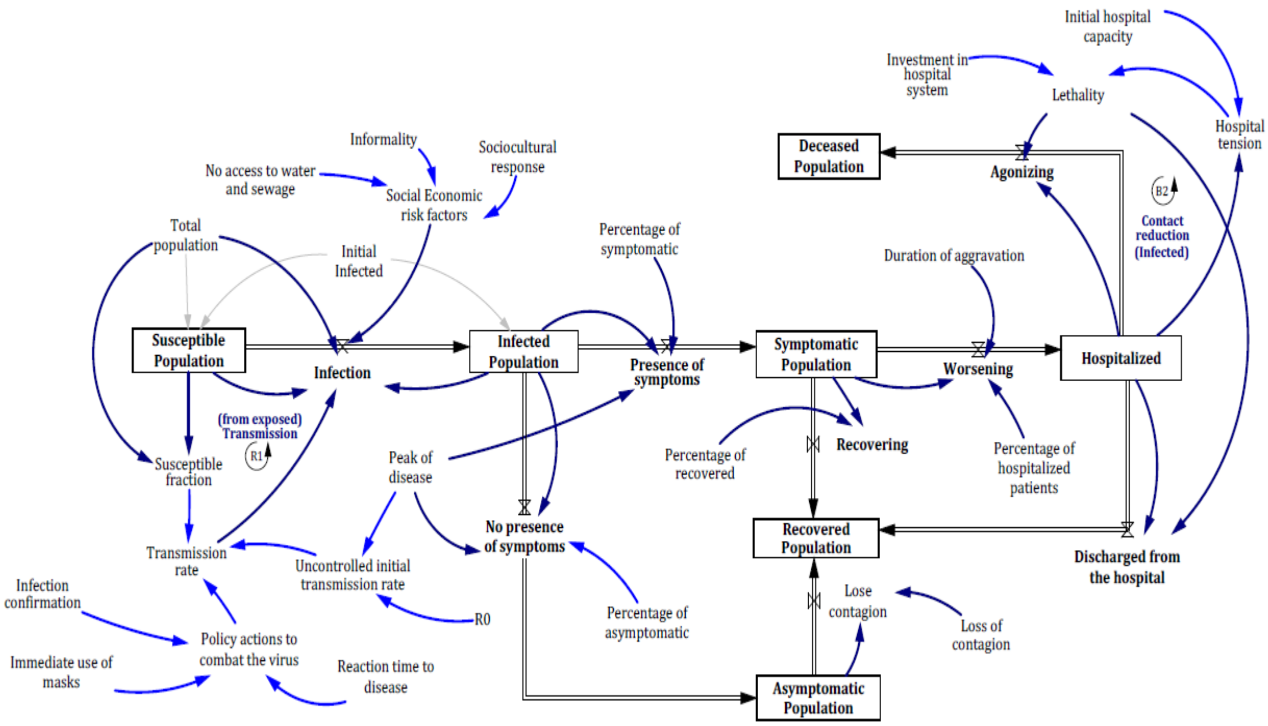
Thus, **Recovered Population (*R*)** is positively affected by people who are recovering (*RE*) from mild and moderate symptoms, those who lose contagion (*PC*) after being asymptomatic and those who have overcome a severe case, being discharged (*DA*).

$$R'(t) = PC + DA + RE \qquad persons \qquad (21)$$

Finally, the level variable **Deceased Population (*F*)** is positively affected by the number of people in agony (*AA*). The number of people in agony can increase or decrease according to the case fatality rates (*Lt*) and thus accumulate a greater or lesser number of deaths from the disease.

$$F'(t) = AA \qquad persons \qquad (22)$$

Figure 6. Forrester Diagram of Covid-19 in Peru



ANALYSIS OF RESULTS

Before the experiments, it has been verified whether the behavior generated by the proposed model represents reality. For this purpose, the quantities reported by official Peruvian government institutions on the behavior of Covid-19 were used as reference mode. The indicators taken as a reference were mainly the infected population, hospitalized population and deceased population.

Likewise, by means of the experiments, a sensitivity analysis was carried out to study and learn which parameters have the greatest influence on certain variables and thus achieve a better understanding of the behavior of the model.

The reference mode covers a period of 260 days, from March 31 to December 16, 2020. We strategically included 9 key variables to perform an in-depth analysis, with the objective of analyzing whether they are variables that significantly affect the spread of the virus. The set includes policy actions to combat the virus: confirmation of infection, immediate use of masks and reaction time to the disease; social risk factors: informality, lack of access to water and sewerage, and sociocultural response; as well as health factors: investment in the hospital system, initial hospital capacity and hospital tension.

To begin with, it should be noted that as of March 31, there was already a certain number of infected, deceased, hospitalized and recovered: 1065, 30, 238 and 394 people respectively. These were considered in the simulation as initial data.

In this sense, when carrying out the simulation we have obtained results close to those reported in formal media such as MINSA (National Center for Epidemiology, Prevention and Disease Control, 2020). According to the quantities of the COVID-19 situation in Peru, for August 14 (day 136 of the period) there were 13 947 hospitalized patients, of which 1 540 were in intensive care (UCI) with mechanical ventilation (Giles, Kike; 2020).

Compared with the reported data, we observed a minimal variation between the results because in the simulation carried out, we obtained 13 583 hospitalized.

From now on all figures, "notified" means "real data". Analyzing a closer date, we observe that on November 16, corresponding to the 230th day of the pandemic, there were 41 334 infected and 35 177 deaths (Unique digital platform of the Peruvian State, 2021). In this way, when carrying out the simulation, we obtain for 230^{th} day 40 800 infected people, on the other hand, 34 577 people died (*Figure 7*). Comparing the figures of the simulations with the reported figures, we find that the variation between these figures is small (*Figure 8*). Therefore, it can be said that the proposed model contains an acceptable degree of precision with respect to the reference mode.

Experiment 1: *Sensitivity of the parameters of political actions*

We consider a supposed optimistic scenario, for which we modify the following variables: reaction time to disease (*Tre*) it decreases from 10 to 4 days; and the R0, which describes the intensity of an infectious disease, decreased from 2.05 to 1.9.

According to the simulations, a change in the reaction time to disease can be observed, due to the preventive measures, and other variables, it has determined a more favorable scenario. This is because the number of people infected was reduced (C), as well as those hospitalized, and consequently, the deceased. Compared with the reported data, in this scenario, for day 136 there are only 5 440 hospitalized, as well as for day 230 there are 25 743 deaths. It should be noted that the increase in disease takes more days, because infections begin to increase from day 100. By this, we realize that the government would have had a longer term to equip the country with the necessary implements to combat this pandemic before the situation became extreme.

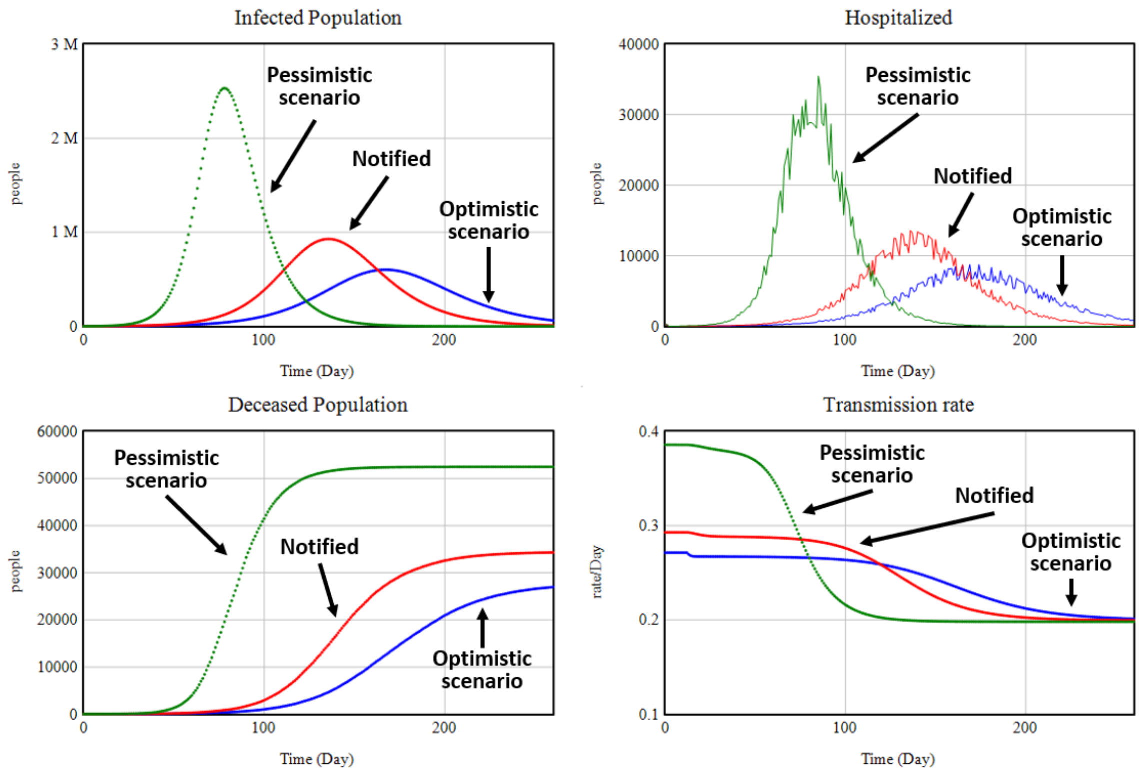
Based on the results, we can say that making decisions at an early moment (variable reaction time to disease) will significantly influence the damage that the disease can cause.

On the other hand, we modified values of the same variables, but taking them to an extreme negative state, where there was no clear strategy to face COVID-19. In this context, we assume that the government did not give importance to the first infected, therefore, the reaction time to disease occurred after 15 days. In addition to this, it is known that the pandemic is reduced and controlled as long as it is possible to keep the value of R0 less than 1. Therefore, because it is a pessimistic scenario, we increase the R0 from 2.05 to 2.7.

Unlike the optimistic scenario, in this scenario, the most critical moment of the pandemic comes in the first 100 days, due to the rapid contagion. That is why the peak of infections occurs on day 78, with 2 533 000 infected. On the contrary, on day 230, there are only 133 infected and on day 136, there are only 1 885 hospitalized, because the disease is already in decline. Even so, the result of the deceased was discouraging, since on the 230th day of the pandemic 53 390 deaths is assumed.

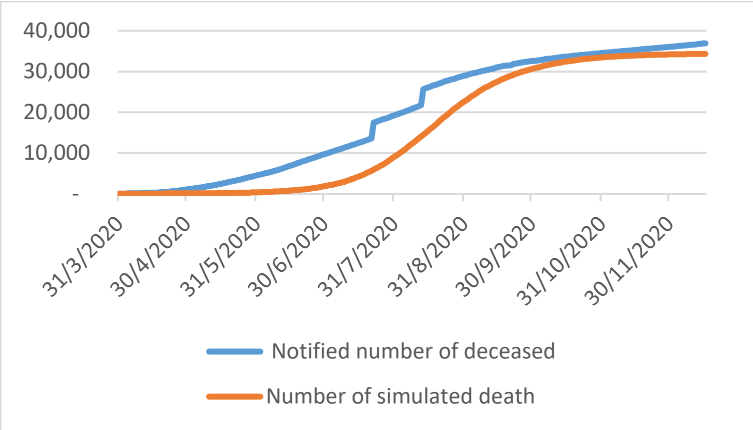
Once the simulations have been analyzed, it can be pointed out that without a quick response from the government when confirming and reacting to the disease, the measures taken against the pandemic are seriously influenced; therefore, more crowds and less awareness of contagion are generated. The sum of these factors will result in the R0 factor increasing; in such a way, that contagion increases. In short, COVID-19 could not be properly controlled and had a tragic outcome when the parameters changed. In *Figure 7*. the results of the experiment are shown, modifying parameters of political actions.

Figure 7. Experiment results N°1: Sensitivity of the parameters of political actions



Note: Horizontal axis: 0 = March 31 2020; 136 = November 16 2020; 260 = December 16 2020. Results of the Covid-19 indicators in Peru, when changes are made in the parameters of political actions: Reaction time to disease (Tre) y RO.

Figure 8. Experiment results N°1: Comparison of notified deaths versus simulated deaths



Note: Horizontal axis: day 0 (March 31)= 35 317 vs 33 961; day 136(November 16)= 36 901vs 34 313 (Unique digital platform of the Peruvian State, 2021).

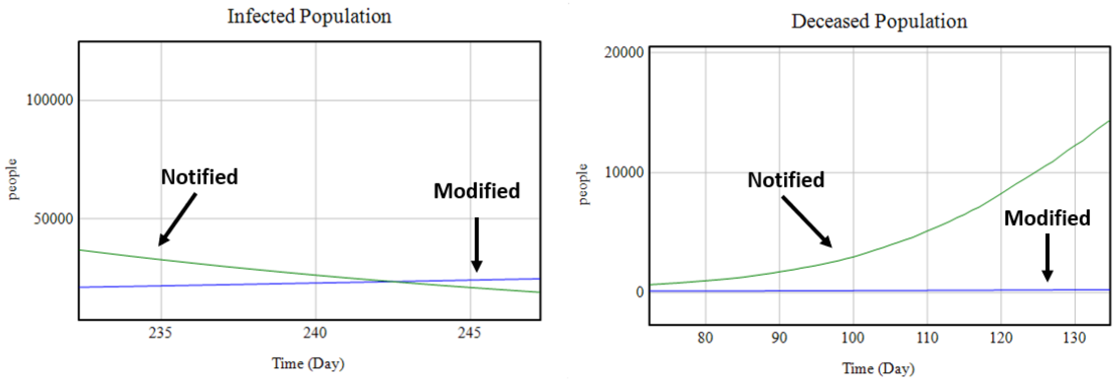
Experiment 2: *Sensitivity of socioeconomic risk factors*

In the following, we analyze the effect of the hypothetical changes in social risk factors, which have been present since before the pandemic, and this made them more noticeable in the Peruvian reality. In this way, we will quantitatively understand how the socio-economic situation of citizens affects compliance with disease prevention measures such as social distancing, use of masks and hand washing. This is reflected in the informality and the need to obtain food and a good quality of life every day.

We begin by modifying three parameters and we carry out a sensitivity analysis of the number of infected due to the following changes: the percentage of informality in Peru (*If*), percentage of people without access to water and sewerage (*Sa*) and the sociocultural response (*Rs*).

The informality variable went from having a value of 0.885 to 0.6, no access to water and sewerage from 0.357 to 0.225 and sociocultural response, which is explained as the probability of contagion among people who do not wear masks, decreased by 10%, that is, to 0.8. After making the mentioned modifications Variations were observed in the number of infected and deceased. In the case of infected, it decreased by 50.01%, since it went from 40 800 to 20 403 infected on day 230. On the other hand, the number of deaths fell by 97.74%, from 34,576 to 780 deceased persons (*Figure 9*). According to these results, we can infer that social risk factors have a great influence on the development of COVID-19 in Peru, since when making the aforementioned modifications, a great variation in the results is observed and this reveals the degree of influence that generate.

Figure 9. Experiment results N°2: Sensitivity of socio-economic parameters



This scenario would explain the unexpected results despite an apparently timely reaction to strict quarantine measures. Our socio-economic reality, the poverty translated into the lack of basic water and sewage services and the economic situation of a sector of the population that is informal, would justify the resistance to correctly comply with the measures imposed by the government.

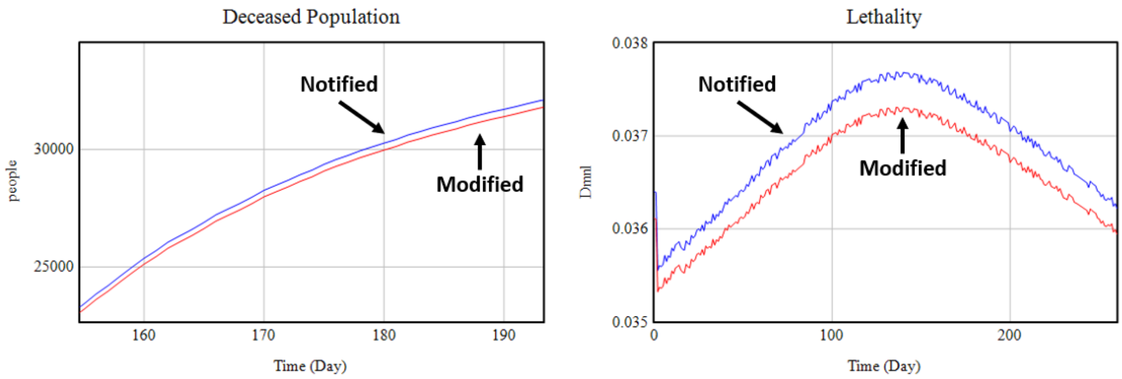
This means that the Peruvian government did not take into account that there are social and economic factors that may help explain why Peru is still in a constant struggle to contain the spread of the virus and prevent the number of infected people from increasing.

Experiment 3: *Sensitivity of health factors*

We analyze the effect of hypothetical changes in health factors, taking into account the situation of hospitals and health centers in Peru. The hospital gap encompasses 4 important things: hospital infrastructure, equipment, medical and paramedical professionals; and medications It is true that, before the arrival of the virus, there were problems with respect to the aforementioned because there were very few optimization investments in hospitals and they became much more notorious during the pandemic, since, hospitals did not have the capacity and complete medical service. However, COVID-19 has been a pandemic that has put the health systems of many countries in the world to the test, despite immediate reactions and decisions based on public health, the death toll was significant.

We changed the hospital system investment variable from 0.89% to 0.95% and the hospital capacity to 70% initially, that is, there was a large amount of UCI capacity (severe cases). We can see that it has not had a great impact on the death toll and the fatality rate. In the realistic scenario (exp. 1), the number of deaths on day 230 was 34 576 and in the best of cases with the modified variables, is 33 961. (*Figure.9*)

Figure 9. Experiment results N°3: Sensitivity of health factors



It can be inferred that the measures taken by the state at a certain moment were wrong, a more central hospital approach was proposed than preventive and did not obtain positive results. This can be seen in the experiment 1, by modifying the reaction time to the disease given by the preventive measures, a much more significant decrease in the number of deaths is observed compared to the results obtained in this experiment. Well, in the preventive stage for the day 230 the death report was 25 743 and in the reactive stage, 33 961. Based on the results obtained, the strategy to overcome the pandemic in the country and obtain better results is the approach in public health measures and daily preventive measures to slow down the spread of the virus.

CONCLUSIONS

The mathematical model designed achieved an acceptable accuracy in relation to the reference mode considered in the sensitivity analysis experiments; it also represents how the different prevention policies, social-economic factors and the improvement of hospital infrastructure in the country interact with other system variables and generate effects that explain the spread of COVID-19 in Peru.

In experiment 1 demonstrates that a change in the government's reaction time parameters, translated into better management of preventive measures, would have led to a reduction in the infection rate. While it is true that there was a timely reaction by the government in terms of a strict quarantine, not enough preventive measures were considered that could guarantee a favorable and permanent response even after the strict quarantine was lifted.

In experiment 2 has made it possible to determine the degree of influence of social risk factors. Relevant variables in this area are informality, the sector of the population without access to water and sewage, and the sociocultural response. Each of these have been modified and have been shown to have a considerable influence on the results. Therefore, it can be said that if Peruvian government decision-makers had known the impact of the aforementioned variables, measures and resources would probably have been focused on substantially reducing these factors. We believe that the creation of more formal jobs, the increase of water access points to more communities in a progressive manner, as well as a better socio-cultural response, influenced by raising people's awareness through the media, would generate favorable results in the curves of contagion and deaths.

In experiment 3, the reinforcement of investments in the hospital system and hospital capacity was modified. While it is true that this allowed us to attend many more mild and severe cases, it is not a major factor because it did not significantly reduce the number of deaths, as shown in the simulation. On the contrary, the outbreak of the virus in the population was so rapid that hospitals collapsed, and even if hospital investment in Peru had been increased to a greater extent in 2020, it would not have been possible to attend all severe cases and provide each one with an ICU bed. Therefore, we point out that a considerable reduction in the number of deaths in the country would not be a consequence of the improvement of hospital infrastructure.

In general, we can test the hypothesis and conclude that system dynamics has allowed us to determine the main factors that can significantly influence the behavior of COVID-19 in Peru, being the variables related to prevention (reaction time to the disease, number of secondary infections of an infected individual, informality, lack of access to water and sewage and socio-cultural response) the most relevant; while reactive factors (such as investments in the hospital system and hospital capacity) failed to prevent the infection of people and consequently the increase in severe cases and number of deaths.

Finally, with what we have studied, we realize that, even so, there are still open questions for future analysis. For example, the political crisis of the country that generated agglomerations in the streets while marching for democracy, as well as the corrupt authorities that seek their benefit instead of fighting the pandemic, etc. However, knowledge of the main factors that influence the behavior of COVID-19 in Peru, as well as access to models that more accurately represent the complex reality of the problem, can contribute to making better decisions, to designing comprehensive strategies that contemplate prevention plans to deal with pandemic situations such as the one we are experiencing, to finding better policies for action and to reduce the negative effects that any future pandemic will have on our population.

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APPENDIX A

This section shows the table of the level variables, flow and auxiliary variables. In the following Table 1 the fundamental level variables are detailed.

Table 1. Level variables

Shrt	Name	Units	Definition and justification
S	Susceptible population	persons	People who are in a state in which they are susceptible to contracting the disease, the person can be infected for another infected person.
C	Infected population	persons	People who test positive for COVID-19 and can transmit the virus.
SI	Symptomatic population	persons	Infected people who present symptoms of mild or moderate intensity, such as, for example: Fatigue, headache, dry cough, etc.
AS	Asymptomatic population	persons	People who have contracted COVID-19 and have no symptoms of the infection.
H	Hospitalized	persons	People infected for COVID-19, who have treatment and need medical attention, because they are in a serious and decisive situation.
R	Recovered population	persons	The people who have overcome the disease and are not contagious.
F	Deceased population	persons	Patients who did not get over the coronavirus, and eventually die from the disease.

In the following, Table 2 shows the 8 flow variables that allow us to explicitly express the variation of the levels per unit of time.

Table 2. Flow Variables

Shrt	Name	Units	Definition and justification
I	Infection	persons /days	Transmission of covid-19 by an infected agent to an uninfected agent.
SS	No presence of symptoms	persons /days	People who have been infected, but who do not have symptoms such as: fever, dry cough, difficulty breathing, loss of smell or taste, etc.
CS	Presence of symptoms	persons /days	People who have been infected, and have symptoms such as: fever, dry cough, difficulty breathing, loss of smell or taste, etc.
AG	Worsening	persons /days	People who have developed COVID-19 to be severe and are about to require intensive care or hospitalization.
RE	Recovering	persons /days	Stage where symptomatic patients, who have not presented serious symptoms, recover without the need for hospitalization.
PC	Lose contagion	persons /days	Asymptomatic people who are losing coronavirus antibodies.

DA	Discharged from the hospital	persons /days	People who have overcome a critical condition, and have recovered from the disease.
AA	Agonizing	persons /days	The situation that precedes the death of the patient due to the severity of his health.

Likewise, Tables 3 and 4 also list the twenty-five auxiliary variables. Table 3 shows the variables initialized with constant values or parameters and Table 4 shows the auxiliary variables defined by means of mathematical expressions, respectively.

Table 3. Auxiliary Variables - Parameters

Shrt	Name	Initial Value	Units	Definition and justification
Ci	Confirmation of infection	10	days	Based on literature. Time from the first infection of COVID-19 to the confirmation of the disease in Peru. He is considered the first imported case of COVID-19 (Redacción Gestión, 2020).
PT	Total population	32 625 900	persons	Based on literature. Inhabitants of Peru in 2020 (INEI, 2020).
ii	Initial infected	1065	persons	Based on literature. Number of people infected at the beginning of the pandemic (Unique digital platform of the Peruvian State, 2021).
Tre	Reaction time to disease	10	days	Based on literature. Time from first infection for government to fully implement total quarantine (As.com, AS Peru, 2020).
im	Immediate use of masks	0.015	dmnl	Based on literature. Percentage of possible contagion with the correct use of masks between two persons (Empresa Peruana de Servicios Editoriales S. A. EDITORA PERÚ, 2020).
Epico	Peak of desease	7	days	Estimated. The peak of the disease is between five and seven days after infection.
R0	R0	2.05	dmnl	Based on literature. Expected number of secondary infections derived from a single infected individual during the infectious period in a fully susceptible population. The plausible range reported for coronavirus is about 1.5-2.7 (Huamaní C, Estimated conditions to control the COVID-19 pandemic in pre- and post-quarantine scenarios in, 2020)
Pas	Percentage of asymptomatic	0.2	dmnl	Based on literature. Percentage of infected persons who do not present any COVID-19 symptoms. (National Center for Epidemiology, Prevention and Disease Control, 2020).
PerC	Loss of contagion	15	days	Based on literature. Time it takes for the covid-19 virus to disappear in asymptomatic persons. It is not a proven fact, but it is estimated to be between 15-16 days. (As.com, As.Peru, 2020).
Ps	Percentage of symptomatic	0.8	dmnl	Based on literature. Percentage of people who, once infected with COVID-19, do develop symptoms (Ríos, Gestation in times of a coronavirus pandemic, 2020).

Ph	Percentage of hospitalized patients	0.25	dmnl	Based on literature. Percentage of people symptomatic of the disease, who are in a serious condition and become hospitalized (La Organización Panamericana de la Salud , 2020).
Pr	Percentage of recovered	0.75	dmnl	Based on literature. Percentage of symptomatic people, who only have mild symptoms and do not present a serious condition, and therefore recover from the disease. (La Organización Panamericana de la Salud , 2020).
Sa	No access to water and sewage	0.357	dmnl	Based on literature. Percentage of Peruvians who do not have access to water and sewage services (Servindi, 2020).
If	Informality	0.885	dmnl	Based on literature. Percentage of informal workers in Peru (Julio Lira Segura, 2020).
Rs	Sociocultural response	0.9	dmnl	Estimated. Percentage of Peruvians who, due to their idiosyncrasy and lack of awareness, do not comply with protection measures.
Da	Duration of aggravation	7-10	dmnl	Estimated. Random Uniform. Duration of infection, once in a serious condition.
Ch	Initial hospital capacity	0.04	dmnl	Estimated. Measurement of initial ICU bed stock in hospitals.
Is	Investment in hospital system	0.089	dmnl	Based on literature. Money invested by the Peruvian government for the specialized health sector in COVID-19 (IPE, Health sector spending against COVID-19: grew exponentially but is insufficient., 2021).

Table 4. Auxiliary variables

Shrt	Name	Units	Definition and justification
Fs	Susceptible fraction	dmnl	Calculated. Probability of occurrence of people prone to infection, that is, the fraction of the initial population that remains susceptible.
Tt	Transmission rate	rate/day	Calculated. Probability of occurrence of spread of COVID-19 on the day.
Fr	Social economic risk factors	dmnl	Calculated. Coefficient of people who are informal, do not have a mask and do not have access to water.
Ap	Policy actions to combat the virus	dmnl	Calculated. Indicator that expresses the effectiveness of government mitigation measures to stop the spread of the virus.
Ti	Uncontrolled initial transmission rate	dmnl	Calculated. Fractional risk reduction according to preventive measures: social distancing, increased hand washing and others. Indicator that expresses the frequency of uncontrolled transmission of the virus.
Lt	Lethality	dmnl	Calculated. Proportion of people who die from COVID-19 among those affected by it in a given period and area (seriously ill hospitalized). Average 0.0379 (Ognio, 2020).
Th	Hospital tension	dmnl	Calculated. Relationship between the capacity of ICU beds available and the number of hospitalized patients.