Modelling Experiences of the COVID-19 Pandemic in Ibero-America

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Edited by

Carlos N. Bouza-Herrera

Cambridge Scholars Publishing

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AUTHOR

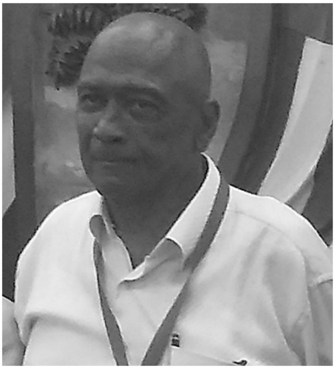

Figure 1: Dr. Carlos N. Bouza Herrera

We are pleased to present the editor–prof. Dr. Carlos N. Bouza-Herrera (CB). He was born and lived in La Habana, Cuba, where he studied at public schools. At the age of 17 he began working at a Cuban Telephone Company and continued his secondary school studies. CB got involved in the tide of political changes that occurred in his country and stopped studying for a while. In 1966 he matriculated in the School of Mathematics of Universidad de La Habana and selected the specialization in Mathematical Statistics. He shared working, studying and politics.

The new Cuban society developed a series of research institutions in medicine and agriculture. The country was urged to have statisticians duly trained. The different university careers now included the teaching of statistics in their curriculums and there was a lack of such teachers. Advanced students of Mathematical Statistics were encouraged to teach and CB got involved, and included these activities in his daily life. Once graduated, he was ubicated in the corresponding department of the School of Mathematics.

Research institutes of the country needed statistical aids, and projects with them were promoted systematically. CB specialized in modeling survey sampling for biologists, engineers and sociologists, mainly. These applications produced several reports as early as 1973. A PNUD-UNESCO project supported the preparation of statistics and computer sciences professors. Prof. Dr. Vitomir Erdeljan was in charge, for 2 years, of working with statisticians. CB was one of the trainees and under his advisory obtained his MSC (1974) in Cuba and PhD (1978) in the ancient Yugoslavia.

CB has directed 69 projects, of which, 2 are still running. He had visited more than 50 institutions around the world, and particularly he made various visits to the Indian Statistical Institute of Kolkata supported by the Third World Academy of Sciences, where he started a long-term cooperation with generations of Indian statisticians. To our knowledge, he has published more than 270 papers, edited or authored more than 30 books, and participated in more than 150 congresses. CB is member of 15 professional societies and networks and acts as a referee or member of the boards of 51 journals all around the world. CB has been awarded with more than 50 awards with diplomas and medals in his country.

AD-Scientific Index - World Scientist Rankings – 2023 reports the scientific impacts of him as follows:

H Index: Total	17, Last 5 years 13	total: 0,765
i10 INDEX Total	Last 5 year	Last 5 years 17, total 0,708
CITATIONS: Total 910	Last 5 years 555	total 0,610

ADSI ranked CB as 33rd in his university, and 113th among the scientists in Cuba.

Our collaboration with CB has a long history. He participated as a teacher in our MSC program and as an advisor of MSC and PhD theses and other research. Collaborating with other institutions, he has been a motivation for developing joint research within networks. Red iberoamericana de Estudios Cuantitativos Aplicados is one of them. This network connects Ibero-America's researchers and French's institutions collaborators and, and they produce yearly a book with results of the cooperation. Note that, though he is pensioned, CB continues actively working both in teaching and investigating, having the leadership of programs, projects and several activities where his experience is needed. This book has been provoked by the work of collaborators of CB on the study of Covid-19.

CB is happily married with Sira Allende and they have a daughter, Gemayqzel. They are mathematicians too. As a person, his sense of humor is proverbial, in good and bad times. That stimulates his colleagues with looking for a solution, when the expected results are not satisfactory. Distressing is innate and in the joint work with his colleagues, friends and relatives, his advises come not as reprimands but as a product of some philosophical reflection. He is prompt to aid everyone, not only in the classrooms or at the research laboratories but also in current life. His experience in living provides to people ideas for solving seemingly too cumbersome problems that new generations have to deal with. We and his network congratulate him and express our wishes of a long life.

Agustin Santiago-Moreno and Jose Maclovio Sautto-Vallejo.

PROLOGUE

The COVID-19 pandemic has posed a set of unprecedented challenges to humanity. The management of healthcare resources should be based on quantitative studies as it has generated a lot of epidemic data. Quantitative modelling allows generalizing which can guide the decision makers. The impact of COVID-19 in healthcare resources is particularly affecting lower and middle-income countries. Latin American countries are disadvantaged due to the lack of medical personal, beds in hospitals and medical supplies. Nonmedical specialists are contributing to the development of quantitative models, which are aiding the study of the COVID-19 pandemic dynamics. Some countries have structured public policies using some mathematical models.

Nowadays, quantitative models, mathematical and simulation mainly, are used for planning and/or evaluating health issues. Recommendations based on quantitative studies improves strategic, tactical, and operational aspects of preparedness planning in the management of the pandemic.

The recommendations derived from the research that generated the chapters of this oeuvre are a significative sample of studies developed in Latin America on the COVID-19 pandemic during 2020.

Chapter I is concerned with the development of an ordinary differential equation model and formulates the expression of Basic Reproductive Number (R_0) for the subpopulation of undetected infected individuals. The authors modelled risk perception through proposed functions and simulated governmental actions and individual attitudes, with a contagion variable rate over time. Real data were used for predicting the behaviour of the pandemic.

Chapter II proposes, discusses and illustrates Agent-Based Modelling to handle complexity and its consequent uncertainty in decision-making processes, based on the law of the dynamic equilibrium of markets and the unlimited rationality of both social and economic agents. They explored and estimated how the establishment of rules for the social behaviour of a community affects the dynamics of an epidemic. An application was developed, in NetLogo, that allows the construction of a model of a city from its basic demographic information: size, population, inhabitants per house, number of closed public areas and amount of free area.

Chapter III is devoted to describing the behaviour of COVID-19 in Mexico from the first confirmed cases on February 28, 2020, until May 2021. This characterization of COVID-19 in Mexico was made through positive cases, cases with comorbidities, number of deaths, mortality rate, incidence rate and fatality rate; represented by state, sex and age group. The analysis of the behaviour of the pandemic in Mexico used the correlation coefficients among three relevant variables against two indices-summaries, for the data of the states. The relevant COVID-19 variables considered were incidence, mortality rate, and fatality rate. The relations analysed were the Marginalization Index and the Human Development Index studied under the conditions of the pandemic, considering the socioeconomic conditions of the states of Mexico.

Chapter IV has considered a supervised multilayer neural network – Artificial Neural Network – for fitting the data of estimated cases of COVID-19 in the State of Puebla. However, this model was inefficient in several cases. The authors developed alternatively a "vectorial" neural network with an unvarying step function activity. A positive defined matrix allowed training the variable learning rate model, using the existing data on the disease, from week 10 of 2020 to week 35 of 2021.

Chapter V has proposed models for post-pandemic studies and the sequels of the treatments. Theoretical models for epidemic graphs were characterized for aiding the epidemiologists in evaluating the effect of treatments (sequels, correlations with demographic variables, etc.). The modelling in the context of COVID-19 was developed.

Chapter VI has considered problems on sampling in the presence of missing observations. The authors established regularities of the expectations under a particular non-response mechanism, considering some issues present in real life statistical research in COVID-19. Imputation procedures and superpopulation modelling have provided a theoretical frame for dealing with missing observations within the framework of sampling, looking for identifying contacts with infected people.

Chapter VII poses a discussion on the effects of the COVID-19 pandemic in increasing the visible inequality in Latin American countries. The authors have developed a study in an especially vulnerable sector of indigenous Mexican students.

Chapter VIII presents a study on hospital-staying in surviving individuals from COVID-19 of Cuban recovered patients living in Havana. The article proposes future lines of research.

In Chapter IX, a prospective pilot study is developed for establishing the behaviour of recovered COVID-19 patients with lung damage treated with a new medicament.

This book provides a good example of the research developed by Latin American scientists for dealing with the challenges posed by the COVID-19 pandemic.

CHAPTER I

MANAGEMENT OF COVID-19 IN CUBA WITH RISK PERCEPTION: A SAIR-TYPE MODEL CONSIDERING THE ASYMPTOMATIC POPULATION

DANIEL MENCIÓ PADRÓN[1],
GABRIELA BAYOLO SOLER[2] AND
AYMÉE MARRERO SEVERO[2]

Summary

Based on epidemic population models defined by ordinary SAIR-type differential equations, this work presents a variant that distinguishes between the populations of uncontrolled symptomatic and asymptomatic infected people, moving freely in society, to represent the transmission dynamics of COVID-19 and the subpopulation of individuals in quarantine and hospitalized, managed by the institutions of the Health System.

It presents the generated diagram for the population model defined by ordinary differential equations. Also, it formulates the expression of Basic Reproductive Number (R_0) for the subpopulation of infected individuals that are not detected, whom are, consequently, the main ones guilty of the transmission of the epidemic.

It shows the obtained results by fitting essential parameters of the models by considering data of Cuba in the first 51 days of 2021. The formulation of risk perception through functions that simulate government actions and

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individual attitudes, with a variable contagion rate over time, allowed us to simulate different scenarios by considering epidemic waves and present useful predictions for efficient actions of the Public Health System and other authorities in order to control the pandemic.

Keywords: epidemic model, SAIR-type, asymptomatic population, infection rate, risk perception.

1. Introduction

In Cuba, the first cases of SarsCov2 infection were reported on March 11th, 2020. Three foreigners arrived in the country from Italy. Before that, the Cuban Ministry of Health and the Cuban scientific community had accelerated studies and strategies addressed to declare COVID-19 a pandemic in the country.

Works presented by researchers from countries around the world provided highly useful information for mathematical modelling. Taking into account the so-called social distancing or isolation as an efficient way to control it, reducing person-to-person contact with the aim of controlling the spread, avoiding high numbers of infected and sick people and, therefore, decreasing the impact and extent of the disease (Gutiérrez and Varona 2020), (Lin and et al 2020), (López 2006), after one year, there is no specific curative treatment to prevent the collapse of health services, either due to lack of resources, both human and material, or due to the complexity of access to vaccines that generate proven immunity; therefore, studies of this nature maintain their value and importance.

The Cuban scientific community has provided a considerable number of mathematical models to describe the transmission dynamics of this disease, which have contributed to design State and Health System control protocols to deal with it.

The papers Chen (2020), Gutiérrez and Varona (2020), Lin and et al. (2020) and Wu, Leung and Leung (2020) motivated the authors of this work to make the initial proposals Marrero, Menció and Bayolo (2020) and Menció, Bayolo and Marrero (2020) variants, called SEAIR and SAIRV, of the classic population type SEIR. The SEAIR model adds the subpopulation of individuals in the incubation or latency period, distinguishing between the symptomatic and asymptomatic infected, considering this latter as a new subpopulation; the SAIRV model considers a variant with exposure to the

virus and the differentiation of asymptomatic and infected people hospitalized, quarantined and moving freely in society.
The results obtained and the intention to refine details that explain and characterize the endemic waves or new outbreaks that occurred in Cuba motivated the proposal of a new SAIR-type variant that, as in the previous models, considers variable transmission rates based on parameters that represent the strength of the control action and the risk perception, keeping, for some of the parameters, the definitions of previous works (Marrero, Menció and Bayolo 2020), (Menció, Bayolo and Marrero 2020). An adjustment of the main parameters that characterize the transmission dynamics and the estimates has been carried out using MATLAB version R2018a, which allowed validation and comparison of results.

2. Mathematically modelling COVID-19 with risk perception

This work shall intend to analyse an infectious disease, overall, in its ability to invade a population.

To describe this effect mathematically, systems of ordinary differential equations are used, among other tools.

The conditions of existence and uniqueness of the solution of a system of ordinary differential equations are based on the classical theorem (Elsgoltz 1969). However, its great applicability to disease transmission processes has supported the formulation of an epidemiological variant of this theorem, valid in a biologically feasible region, which guarantees the non-negativity of the solutions.

Theorem. Let $F\colon \mathbb{R}_+^n \to \mathbb{R}_+^n$ be a locally continuous Lipchitz function and assume that $F_j(x) \geq 0, \forall x \in \mathbb{R}^n\ \forall j = 1,2,\ldots,n$. Then, $\forall x_0 \in \mathbb{R}^n$, there is a unique solution of $\dot{x} = F(x), x(0) = x_0,\ \ x_0 \in \mathbb{R}_+^n$, x_0 belonging to the interval $[a, b]$ with $b \in [0, \infty)$. Demonstration in (López 2006).

These theoretical mathematical results guarantee that the proposed model makes epidemiological sense, within an invariant region in which all the solutions of the system remain non-negative and bounded, $\forall\ t > 0$.

Particularly, in epidemiological models the existence of the infection-free point (in which there is an absence of disease in the population) and a threshold parameter called Basic Reproductive Number (R_0) are both taken into consideration. The (R_0) has great importance in the analysis of transmission. If $R_0 < 1$, infection-free point is asymptotically locally stable, therefore the disease does not invade the population. This indicator could be understood so that, on average, an infected individual produces less than one new infected individual in the course of their infectious period, so the disease does not grow. If $R_0 > 1$, infection-free point is unstable and disease will probably invade the population, since every infected individual produces on average more than one new case, and so disease may become an epidemic (infected population number increases); when $R_0 = 1$, it denotes disease endemism or, at least, permanence in time.

The novelty of this disease is assumed; its short time of development around the world; and the lack of certainty in its medical-clinical and epidemiological behaviour. Therefore, each modelling proposal must take certain hypotheses, essentially related to uncertainty about, for example, period of infectiveness characteristics, antibody count, differentiation of contagion rates between asymptomatic and symptomatic, period of immunity after recovering from the disease, etc.

Based on various international articles (Chen 2020), (Gutiérrez and Varona 2020), (Tang and et al 2020), (Wu, Leung and Leung 2020) and our previous proposals (Marrero, Menció and Bayolo 2020), (Menció, Bayolo and Marrero 2020), we present in this work a new SAIR-type variant with differentiation of free and controlled populations, assuming temporary immunity after suffering the disease and considering variable transmission rates based on parameters that represent the strength of the control action and the perception of risk.

2.1 Model variables

$S\ (t)$: Susceptible population (healthy people in the population at time t)

$A_L\ (t)$: Asymptomatic free population (infected people, not tested at time t, who do not develop symptoms and remain in the population until they are detected or pass the period of infestation)

$I_L\ (t)$: Free infected population (infected people, not tested at time t, who develop symptoms and remain in the population until they are detected, recover or die).

$Q\ (t)$: In quarantine population (people, infected or not, who are confined at time t, either because they are contacts of positive cases or because they are suspected of being infected, until they are tested)

$I_h\ (t)$: Hospitalized infected population (infected people, tested at time t, who remain in this subpopulation until they recover or die)

$R\ (t)$: Recovered population (all people who, at time t, after the infestation period, have recovered from the disease, whether or not they have been hospitalized).

Health authorities do not control subpopulation sS, A_L, I_L, so it may be considered that they are transmitting the virus in society.

Subpopulations Q and I_h are under the control of health and community entities, either in hospitals, isolation centers or under observation at their homes.

It is important to emphasize that, in our conception of recovered people, not only those controlled by health entities, but also those infected (asymptomatic and symptomatic), who freely develop the disease, are taken into account. Another characteristic of the model is that, taking into account the Cuban strategy of management and control of the disease, those recovered with negative tests are returned to confinement for a defined period.

2.2 The model

$$\frac{dS}{dt} = -\frac{S}{N}\left[\beta(t)(I_L + \theta A_L + cP_f) + \beta_c Q + \beta_h I_h\right] - \sigma S + \left(1 - d_Q\right)\tau_Q Q + (1-c)P_f$$

$$\frac{dA_L}{dt} = \frac{S}{N}\beta(t)(1-q)(I_L + \theta A_L + cP_f) - (d_{AL} + \tau_{AL})A_L$$

$$\frac{dI_L}{dt} = \frac{S}{N}\beta(t)q(I_L + \theta A_L + cP_f) - (d_{IL} + m + \tau_{IL})I_L$$

$$\frac{dQ}{dt} = \frac{S}{N}(\beta_c Q + \beta_h I_h) + \sigma S - \tau_Q Q + \gamma_h I_h - \tau_R \gamma_h I_h$$

$$\frac{dI_h}{dt} = d_Q \tau_Q Q + d_{AL} A_L + d_{IL} I_L - (m + \gamma_h) I_h$$

$$\frac{dR}{dt} = \tau_{AL} A_L + \tau_{IL} I_L + \tau_R \gamma_h I_h$$

2.3 Diagram of the model

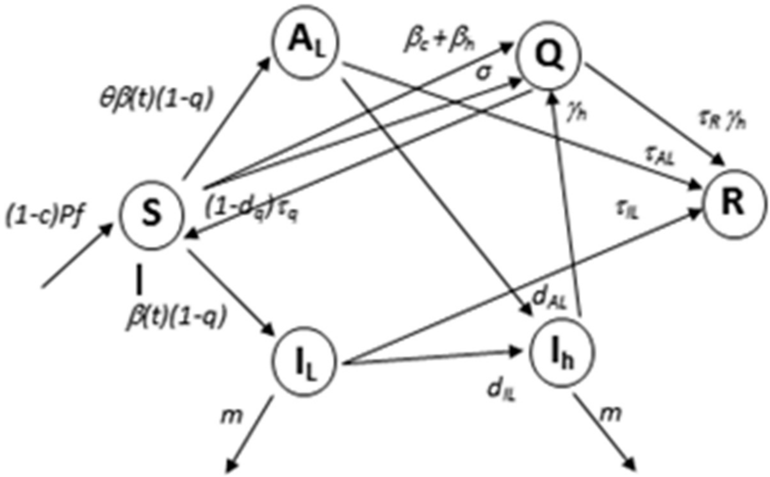

Fig. 2-1. Diagram of the model

2.4 About the Basic Reproductive Number R_0

To calculate the indicator R_0 of the model proposed in this work, the next generation matrix was used, a tool widely reported in the literature for its simplicity and viability (Marrero, Menció and Bayolo 2020). It was obtained that, at the infection-free point, all the variables take a value of zero except S_0, the susceptible population at the initial instant, which coincides with the total population.

Having in mind the characteristics of this disease and its behaviour generate epidemic waves or regrowth, an expression to R_0 variable over time was obtained. This aspect is conditioned essentially by its dependence (among others) on the transmission rate, which is also variable. In the procedure developed to the calculation of R_0, the parameters that determine transmission in subpopulations of free infected people (asymptomatic and symptomatic) and in subpopulations of controlled infected people (in quarantine and hospitalized) were discriminated. This determines that the greatest source of contagion lies in the free infected subpopulation. The following expression for R_0 parameter characterizes these subpopulations and strongly influences all transmission:

$$R_{0L}(t) = \beta(t)\left[\frac{(1-q)\theta}{(d_{AL}+\tau_{AL})} + \frac{q}{(d_{IL}+m+\tau_{IL})}\right]\frac{S_0}{N}$$

2.5 Model Parameters

P_f: Floating population entering the country. It is generated as a random number, bounded in a certain interval, taking into account the analysis of the available data.

σ: Proportion of suspects and people under observation. In the protocol for coping with COVID-19 in Cuba, the so-called "epidemiological spider" (also known as contact tracing) is established to isolate and control, during a period of time established by the characteristics of the disease, all the possible contacts of the detected infected person.

θ: Transmission constant for asymptomatic patients.

c: Proportion of infected people.

γ_h: Recovery rate in hospitalized patients who suffered from the disease

d_i: Positive detection rate for each subpopulation, for $i = Q, A_L, I_L$. It represents the proportion of individuals detected positive with confirmatory tests such as PCR, antigen test, etc., which motivates their confinement or hospitalization.

τ_Q: Infectiousness rate in inmates

τ_{AL}: Infectiousness rate in non-controlled asymptomatic people

τ_{IL} : Infectiousness rate in non-controlled infected people

τ_R : Infectiousness rate in recovered patient

With $\tau_i = \frac{1}{p_i}$ for $i = Q, A_L, I_L, R$; where p_i represents the infectious periods according to subpopulation.

m: Death rate from disease

The transmission rate of diseases under study is commonly considered as a more invariant parameter over time. However, in this model, as in the previous proposals (Marrero, Menció and Bayolo 2020), (Menció, Bayolo and Marrero 2020), this rate is considered as a variable function over time, a result that also appears in recent works on this subject.

$\beta(t)$: Infection or transmission rate in free infected populations (asymptomatic and symptomatic)

$$\beta(t) = b_0(1-\alpha(t))\left(1-m\left(\frac{I_h + I_L}{N}\right)\right)^k$$

$\alpha(t) = 1 - e^{-\delta t}$ represents the strength of the actions in the face of risk perception.

β_c, β_h: Contagion or transmission rate in confined and hospitalized populations respectively.

$\beta_c(t) = b_{c0} * (1-\alpha)(1-\rho * dp_Q Q)$, $\beta_h(t) = b_{h0} * (1-\alpha)(1-\rho I_h)$,

where ρ defines the coefficient of transmission adjustment.

3. Estimation of the model parameters

In obtaining acceptable results, it is indispensable to have reliable values of the essential parameters that characterize the transmission dynamics. For this reason, the parameter estimation problem for models described by ordinary differential equations is addressed, formulated as an optimization problem associated with finding the vector of optimal parameters in the model in question, minimizing the norm of the relative residual error between the actual data with the estimates obtained at each instant of time. Therefore, following the function, it's been defined:

$$e_i = \left\|\frac{X_{dat}(t_i) - X_{EDO}(t_i)}{X_{dat}(t_i)}\right\|_2, i = 1, \dots, n$$

to minimize $W = \sum_{i=1}^{n} w_i e_i$, where w_i represents the weights, $X_{dat}(t_i)$ vector of data from the variables of the model at each instant of time and $X_{EDO}(t_i)$ the corresponding estimates.

In this work, a strategy of hybridizing the Simulated Annealing heuristic with Quasi-newton methods, implemented in MATLAB, has been used to find the vector of optimal parameters, in order to refine the starting point for the classical optimization methods with functions like *fminsearch* and *fmincom*.

Best results were obtained using MATLAB function *fminsearch*, considering the three variables of the model for which data were available and adjusting the model for the first 51 days of the epidemic in 2021. During adjustment, the function $\alpha(t)$ was defined as follows:

$$\alpha(t) = \begin{cases} 1 - e^{-\delta_1 t}, & 0 \le t \le 37 \\ \dfrac{1 - e^{-a_1(t-37)}}{a_2}, & 37 < t \le 41 \\ 1 - e^{-\delta_2 t}, & 41 \le t \le 48 \\ \dfrac{1 - e^{-a_1(t-41)}}{a_2}, & 48 < t \le 50 \\ 1 - e^{-\delta_1 t}, & t > 50 \end{cases}$$

From a numerical point of view, it is difficult to obtain valid results when the number of parameters is too large. Overall, comparing the number of variables in the model and the available data. Therefore, a certain number of parameters to be estimated is chosen and others are taken from the literature, as the opinion of specialists or according to reliable publications. Table 3.1 shows the parameters that were estimated in this investigation, the rest was taken from (Marrero, Menció and Bayolo 2020) and (Menció, Bayolo and Marrero 2020). The average value of the floating population was estimated to be around 455 people. Moreover, although the theoretical model discriminates between the detection rates according to the population, in the experiments d parameter was considered the same one for all the subpopulations.

Parameter	Value
d	0.0234451293424371
σ	0.00168771213544432
τ_Q	1.10742371672635
τ_{AL}	0.0248074364657216
τ_{IL}	0.0524177536853999

τ_r	0.595379115159391
b_0	0.0203526228007360
b_{h0}	0.000515051376863783
b_{c0}	3.81591585158797
δ_1	0.138436211668359
δ_2	0.0682671745032089
a_1	-3.94988438426982e-6
a_2	2.12238077138776

Table 3-1. Estimated parameters.

4. Analysis of Results and Preliminary Conclusions

In previous works (Marrero, Menció and Bayolo 2020), (Menció, Bayolo and Marrero 2020), data from approximately the first three months of the pandemic in Cuba were used, a period in which the pandemic was successfully controlled with predictions for 150 days, when the beginning of a second regrowth began to manifest.

These results conditioned a new epidemic wave in the year 2021, among other factors, such as the reopening of international borders in Cuba in November 2020 and the festive activities at the end of the year. In this proposal, we handled the data of the first 51 days of the year 2021, considering $\alpha(t)$ as defined before, with the estimated values of δ parameter, which characterizes the actions based on risk perception and on which the transmission rate $\beta\ (t)$ essentially depends. This allowed us to simulate a new outbreak with figures much higher than in all of 2020 and to present estimates considering data for the first 51 days of the year 2021.

The figures 4.1, 4.2 and 4.3 show the results for Hospitalized, Quarantined and Recovered variables of the model for the first 51 days of this year. Those are consequence of the Parameter Estimation Problem explained above.

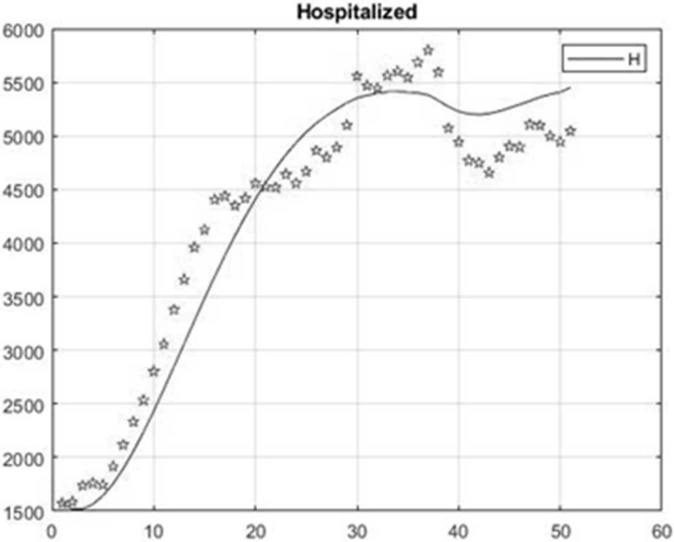

Fig. 4-1 Estimation of the hospitalized subpopulation at each instant of time. The red stars represent the data available in the first 51 days of the year 2021.

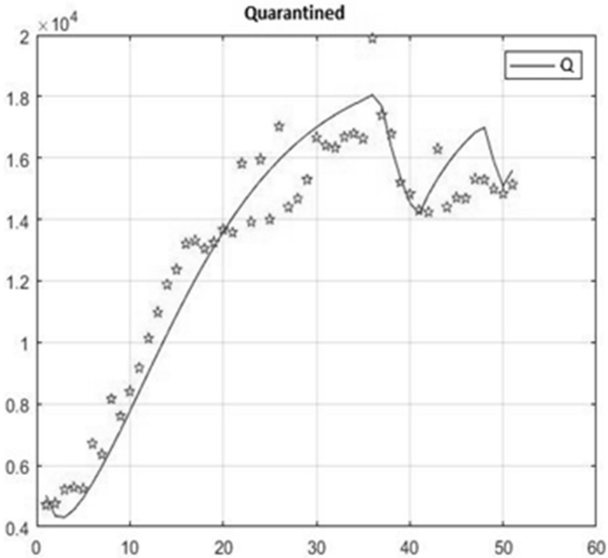

Fig. 4.2 Estimation of the subpopulation in quarantine at each instant of time The red stars represent the data available in the first 51 days of the year 2021.

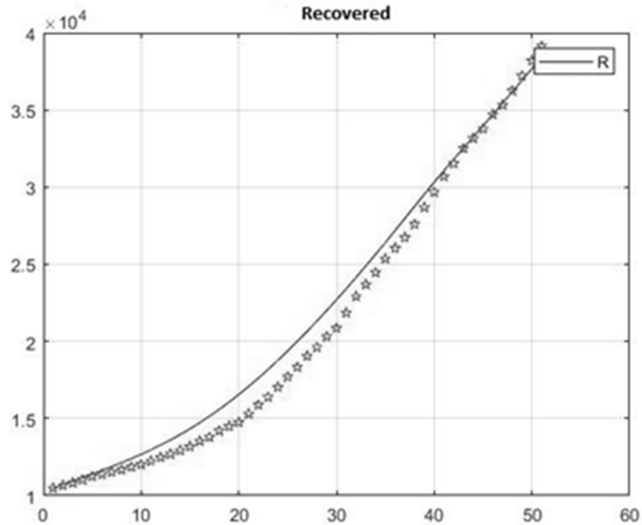

Fig. 4-3 Estimation of the recovered subpopulation at each instant of time. The red stars represent the data available in the first 51 days of the year 2021.

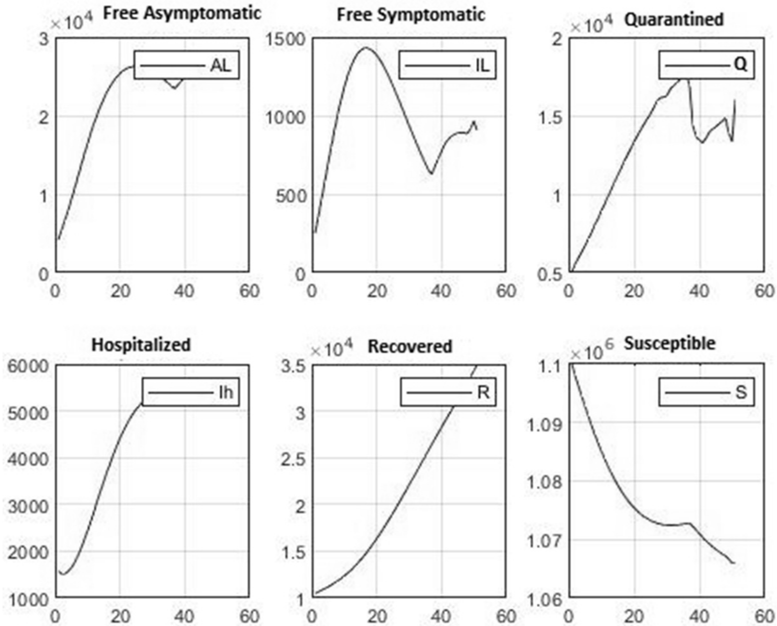

Fig. 4-4 Estimates for each of the model variables

An analysis of Figure 4.4 allows us to understand the influence of each variable on the behaviour of the others. Note that the A_L subpopulation reaches a maximum value close to 29 thousand. Therefore, it is the variable that reports the largest number of patients and yet it is the one with less information.

In order to predict the future behaviour of the hospitalized infected people variable, which is the most interesting for the health system, different possible scenarios were handled for this subpopulation in a period of 150 days after the analysed data. Different expressions were taken into account for the parameter $\alpha(t)$, which characterizes the actions based on risk perception and on which the transmission rate $\beta(t)$ depends, with the intention of simulating situations of greater and lower rigor in the measurements of control.

We worked with the following expressions of $\alpha(t)$, whose behaviours are represented in Figure 4.5.

$\alpha_1(t) = -t^{1/d}$, which simulates a scenario of greater control and perception of risk, therefore, the most favourable (red colour).

$\alpha_2(t) = -t^{1/d}$, which simulates a scenario of less control and perception of risk, therefore, the less favourable (green colour).

$\alpha_3(t) = asen(bt) + c$, which allows simulating a situation closer to the oscillations and regrowth that occur commonly (blue colour).

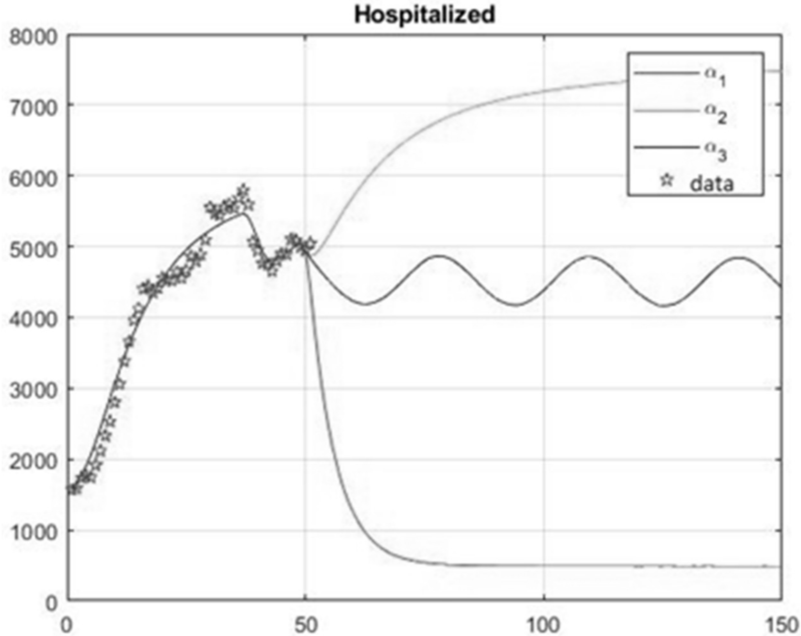

Fig. 4-5 Simulation of the hospitalized subpopulation for the next 150 days, based on the estimates corresponding to the first 51 days of the year 2021.

Using the Parameter Estimation Problem, the behaviour of model variables could be predicted, specially in the short and medium term. This proposal keeps in mind factors that pay to the perception of risk from the individual action as government measures, which are indispensable for the handling of the pandemic.

The different values of parameter $\alpha(t)$, explained previously, allow the simulation of various scenarios related to the perception of risk. In the figure 4.5, these situations are demonstrated for the Hospitalized Subpopulation, which is one of the most important for the Healthy Public System in our country.

The obtained results confirm that the control actions are the principal fact to manage the disease, although, according to the data of this outbreak, a number of sick people will certainly always remain.

5. Final remarks

In this work, a SAIR-type model is presented to simulate the transmission dynamics of COVID-19. Particularly, it subdivides the asymptomatic and infected populations that are non-controlled in society and differentiates between confined and hospitalized people from those who are controlled and attended by the instances of the Cuban Public Health System. During modelling, some of the precepts that characterize the protocol in coping with the disease in our country were represented.

The Parameter Estimation Problem was solved to find the optimal values of the main parameters that characterize the transmission dynamics. To achieve this, a classic optimization problem was formulated, with a minimum-square objective function weighted by the lack of data for the variables of free infected population, both symptomatic and asymptomatic. The satisfactory results obtained with respect to the data of the first 51 days of the year 2021 allowed the simulation of and infer the immediate future behaviour of the disease, in a period of 150 days for the variable hospitalized infected population.

A valid characteristic of the presented proposal is to consider the transmission rate variable and dependent, among others, on factors that simulate the strength of government actions, of health entities and the risk perception of the population. This explains the sensitivity of the results to the variations of these factors. In the case of the hospitalized infected subpopulation, strategies have been used to allow simulating different behaviours, depending precisely on the strength of the control actions. The control of the free asymptomatic subpopulation is essential, since this subpopulation contributes to the largest number of patients and, therefore, characterizes the greatest spread of this disease.

It is known that the results obtained when solving the problem of estimating the optimal parameters depend on the choice of the model, which in turn gives feedback to the modelling process. Therefore, any result is not definitive, but rather contributes to simulate a behaviour close to reality.

The sensitivity of the non-linear optimization methods with respect to the choice of the initial points, in their convergence to local minima, was the reason for the hybridization of the Simulated Annealing metaheuristics with classical Quasi-newton-type methods to solve the parameter estimation problem. It was programmed in MATLAB language version R2018a with the use of units such as *fmincom* and *fminsearch*.

The investigations carried out and the results obtained are still partial and preliminary and will require strategies to refine the data set, which in the present regrowth are not particularly smooth. Therefore, the use of statistical techniques and data analysis is required to provide definitive conclusions. However, what is presented here has an intrinsic value, since it has contributed and still contributes to provide various and multiple tools for decision-makers understand and control epidemic processes, in particular the COVID-19 pandemic caused by the SarsCov2 virus, for the sake of national public health in Cuba and in the world.

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CHAPTER II

USE OF AGENT-BASED MODELLING FOR DECISION-MAKING IN PANDEMIC CONTROL: COVID-19 CONTEXT. APRIL 2021

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Abstract

The available indicators about the way in which the pandemic has evolved in different countries allow us to infer a great diversity of results. Without going too deep, some outstanding scenarios are observed, for which the effects produced by these regulations are distributed in a wide spectrum: at opposite ends, countries like Cuba have established strict measures with strong sanctions, while in countries like Brazil the established measures were lax with low compliance control. In the intermediate zone, there has been a diversity of nuances in the state regulation imposed over the citizen's behaviour regarding the restriction of individual freedoms and of various economic activities.

To date, the results show in some cases a strong impact of the measures on the dynamics of the pandemic, while in other cases this impact has been almost nil (for example, Colombia and Mexico). This reflection strongly motivates a revision of both: employed techniques and the theoretical paradigms from which the different regulations are formulated. For

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