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APPLICATION OF THE SIR MODEL TO COVID-19: social distance and (no-)evolution of the pandemic in state of the Tocantins

APLICAÇÃO DO MODELO SIR À COVID-19: distanciamento social e (des)evolução da pandemia no Tocantins
APLICACIÓN DEL MODELO SIR A COVID-19: distanciamiento social y (des)evolución de la pandemia en el estado de Tocantins

Élis Gardel da Costa Mesquita
Doctor of Mathematics (Universidade de Brasília - UnB). Professor of the Mathematics Network Master's Program of the Universidade Federal do Tocantins (UFT). elisgardel@uft.edu.br.
0000-0003-2385-4108

Janeisi de Lima Meira
Doctor of Science and Mathematics (Universidade Federal do Pará - UFPA). Assistant Professor at Universidade Federal do Tocantins (UFT), in the Mathematics courses and in the Graduate Program in Science and Health Teaching. janeisi@uft.edu.br.
0000-0002-8081-8747

José de Ribamar Leonel Dias Neto
Mathematics Specialist (Faculdade Antonio Propicio Aguiar Franco - FAPAF). Teacher at Instituto Federal de Educação, Ciência e Tecnologia do Tocantins (IFTO). leonel@uft.edu.br.
0000-0001-6319-3063

Mailing address: Universidade Federal do Tocantins, Campus Universitário de Arraias. Avenida Universitária Centro, 77330-000 - Arraias, TO - Brasil.

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ABSTRACT:
This article is a study about the behavior and spread of the Covid-19 pandemic, in the state of Tocantins, based on data reported from March 18 to June 10. A modification of the mathematical model SIR was used, in which some auxiliary compartments were added. We analyzed epidemic aspects such as the speed of the contagion curve and its impacts on the health system. As the data are made available daily, a discretization of the system of differential equations that make up the model was performed, and based on the availability of known data, we investigated the correlation between the social isolation index and the basic reproduction factor. Through a very simple interpolation, approximate contagion rates were obtained, enabling us to evaluate the behavior of the evolution of contagion curves and those that depend on them, which allows us to anticipate scenarios based on the trend lines of the data generated, thus helping decision making public power.

KEYWORDS: COVID-19; SIR mathematical model SIR; Social isolation index; State of the Tocantins.

Introduction

The current planetary emergency experienced recently due to the pandemic resulting from infectious diseases caused by severe respiratory syndromes did not haunt so much before the coronavirus (SARS-CoV-2), which originated the disease of the new coronavirus (COVID-19). The new coronavirus agent was discovered in 2019, after cases recorded in the People's Republic of China on the Asian continent. Studies show that COVID-19 is derived from the SARS-Cov-2 family and was initially found in wild animals, particularly in seafood and bats sold in markets, in the city of Wuhan, in that country's Hubei province. (BENVENUTO, 2020; WHO, 2020).

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The coronavirus has been known since 1937, but it was not until 1965 that it was described as a coronavirus because its profile resembles a crown. Although coronavirus infection in humans is common, it has low lethality occurrences. The lethality rate is a parameter to measure the severity of the disease in a given location/region. However, it does not mean that the person affected by the disease will die, being able to recover and return to their usual activities.

According to WHO (2020), humanity is currently exposed to seven types of coronavirus (HCoVs), namely: HCoV-229E, HCoV-OC43, HCoV-NL63, HCoV-HKU1, SARS-COV (which cause severe acute respiratory syndromes), MERS-COV (which causes respiratory syndrome in the Middle East) and the most recent new coronavirus (which at first was temporarily named 2019-nCoV, and as of February 2020, received the name SARS-CoV- 2). This new coronavirus is responsible for causing the disease COVID-19, whose lethality varies according to the region, in Brazil this rate of approximately 4%.

The severity of the new coronavirus (COVID-19) was declared, in January 2020, by the WHO, as being of "Public Health Emergency of International Importance (ESPII) - which is the highest level of alert declared by that Organization, as is foreseen in the International Health Regulations "(WHO, 2020). This type of emergency warns of the public health risk to other countries of disease due to its international spread, thus requiring coordinated and immediate actions for its control and or treatment in order to prevent worldwide spread. For this case, such concern arises from the difficulty of control and combat due to the high contamination capacity (IHR, 2005) and the transmissibility that can occur, even from asymptomatic cases.

In this sense, the present article consisted of an analysis of the data made available by public health agencies and scientific production about the new coronavirus (SARS-Cov-2), which causes the disease COVID-19. Therefore, the objective was to carry out a systematic analysis based on the application of an epidemiological mathematical model of the epidemic situation of the state of Tocantins, in the northern region of Brazil, with the intention of provoking reflections and debates on the daily life faced by this state since the registration the first case of this disease, thus foreseeing epidemiological situations based on the guidelines of the security agencies and allowing actions by the government.

For this, we constructed a methodological design based on the data made available by the daily epidemiological bulletins published by the Tocantins State Department of Health. We adopted the bulletins published in the interval from March 18, when the first case was registered in the state until June 10, the date of submission of this article, as a

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temporal space. The systematization and treatment of these data took place from the rigorous application of the epidemiological mathematical model SIR, with the aid of the software Geogebra, Solver-LibreOffice, and Calc-LibreOffice to generate the graphs and make some statistical analysis of data.

The analyzes carried out from the application of the epidemiological mathematical model pointed out that the containment measures suggested by the WHO, such as distance and social isolation, basic personal hygiene measures, wearing a mask, testing as a monitoring method contributed to the deceleration of the contagion that is equivalent to the flattening of the contagion curve and thereby avoided the collapse of the health system and funeral services.

From Sars-Cov-1 to Sars-Cov-2

In 2003, the first scientific papers relating a new coronavirus of animal origin to the pneumonia outbreak originating in China with rapid expansion to several other countries in Asia, which occurred in the second half of 2002, were published. The disease was renamed Severe Acute Respiratory Syndrome (Severe Acute Respiratory Syndrome coronavirus - SARS) and the new coronavirus from SARS-CoV or SARS-CoV-1 (CDC, 2003). The main causes for the presence of the new virus among humans were attributed to the accumulation of wild animals in overcrowded spaces at fairs and humid markets coupled with the lack of biosafety measures (WEBSTER, 2004; WOO, 2006).

In addition to its high rate of contagion, the virus had its spread quickly expanded by the large flow of international air travel and the interference of hospitals specialized in infection control. With more than eight thousand infected people around the world and a mortality rate close to 10%, SARS has caused economic, social damage and overburdened the health systems of the affected countries, which characterized it as the first major pandemic of the millennium (DROSTEN, 2003; KSIAZEK, 2003; PEIRIS, 2003).

With the reopening of the wild animal market in southern China in late 2003, there were still a few cases of SARS in very small numbers and with easy control. Around 2006, the discovery of a very similar virus in horseshoe bats, the SARS-CoV bat, implied that a new SARS epidemic could reappear if the conditions for the introduction, mutation, and transmission of this virus remained adequate to jump to humans (CHE, 2006; LAU, 2005; LI, 2005; WANG, 2005).

Despite the warnings, in December 2019, in the city Wuhan in China, it was found, in a patient presenting severe pneumonia, with a new unknown and aggressive virus. Although the origin of the virus is not known, the main suspicions are that it appeared at

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a seafood and wild animals fair in downtown Wuhan. The rapid spread of this virus has caused it to spread to other regions of China. The place of economic prominence that China reached, caused the virus to spread around the world. The disease caused by this new virus was called COVID-19 and the new Sar-Cov-2 virus (new coronavirus).

On March 11, 2020, the World Health Organization declared that the world was experiencing a pandemic due to COVID-19. But this pandemic outperforms the SARS outbreak in 2003 in relative and absolute numbers. As this new disease is not known for its certified treatment, it has caused great economic damage and brought chaos to the health systems of the countries in which it arrived. To stem its advance, drastic sanitary measures were taken and entire economies had to stop.

Because of this, health agencies from all over the world started to create epidemiological surveillance devices, whose intention is to present protective measures aimed at reducing the rapid increase in contamination and minimizing socioeconomic impacts. In Brazil, the Ministry of Health (MS) is the main body responsible for developing policies and actions to face the new coronavirus. As a preventive measure to combat the pandemic, the Ministry of Health created the Plans for the surveillance of Severe Acute Respiratory Syndrome (SRAG) and Flu Syndrome (SG), whose objective was to act in the "identification, notification and timely management of suspected cases of Human Infection by the New Coronavirus to mitigate the risks of sustained transmission in the national territory "(BRASIL, 2020, p. 04).

With the confirmation of the first case on February 26, the Ministry of Health intensified monitoring strategies for this health emergency, intending to change the dynamics of transmission and spread of the disease. Indeed, the mobilization of combat, prevention, and monitoring actions are collaboratively articulated with the states and municipalities and several other bodies, among which we highlight the public universities that develop research, production of protective material, such as PPE, 70% alcohol, masks and actions to guide and prevent transmission concerning the epidemiological picture.

Research space-time: the state of Tocantins

The State of Tocantins is located in the Northern Region of Brazil, with an estimated population, according to 2019, of 1,572,866 inhabitants. It has an area of 277,720,412 km², with a population density of 4.98 inhabitants per km2 (IBGE, 2019). The planning of health services is organized in health regions following the recommendations of Decree No. 7.508 / 11, of the federal government.

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As decree no. 7.508 / 11, the Tocantins territory, is divided into 139 municipalities and distributed in eight health regions, namely: Middle North Araguaia (17 municipalities), Bico do Papagaio (24 municipalities), Southeast (15 municipalities), Cerrado Tocantins Araguaia (23 counties), Ilha do Bananal (18 counties), Capim Dourado (14 counties), Cantão (15 counties), Perfect Love (13 counties). Across the state, there are 19 regional hospitals and 1 contracted philanthropic hospital, which are references for these health regions. In general, these hospitals have differentiated service profiles ranging from general secondary, medium complexity to specialized tertiary, high complexity (TOCANTINS, 2007).

When redefining its territory in health regions, it was necessary to create the Regionalization Master Plan (PDR), which was updated by Decree nº. 7,508, of July 28, 2011 (TOCANTINS, 2007). In which the distribution of health regions throughout the territory is expected, as shown in Figure 1, in order to meet the specificities "delimited from cultural, economic and social identities and communication networks and shared transport infrastructure, in order to integrate the organization, planning and execution of health actions and services" (BRASIL, 2011, p. 1).

Figure 1 Distribution of health regions in Tocantins.

Source: SESAU/TO.

The regionalization of health care decentralizes risk control and monitoring of actions, providing strategic planning, which enhances the attention to the care of the population in the development of good sanitary and epidemiological practices.

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In the context of coping with COVID-19, it should be noted that initially the Government of the State of Tocantins, adopted the measure of social distance, in which it recommended the population to avoid agglomerations, and the minimum distance of one and a half meters between people in places public. With the advancement of COVID-19 cases, social isolation was adopted throughout the state, according to decree no. 6092, of May 5, whose content recommends that people remain in their homes to prevent the spread of the virus, thus establishing the widened social distance. For those suspected of infection, they were instructed to be quarantined for up to fourteen days, which is the incubation period, the period in which the virus manifests itself in the body (FARIAS, 2020).

With the increase in the number of cases in the state, on May 15, Decree No. 6,095/2020 was published, which determined the total suspension/blocking of non-essential activities, known as lockdown, for 33 municipalities, to contain the progress of COVID-19. This measure was determined due to the increase in the percentage of occupancy of hospital beds, public and private, including specific ICUs to care for people diagnosed with COVID-19. After the lockdown period, which lasted 7 days, the state government published Decree no. 6,096, of 22 May, which suspends the lockdown, for the cities in which it was decreed, and retroacts to the effects of decree no. 6,092, of May 5th. These measures allowed a certain breadth to the health system, however, the number of confirmed cases continued to rise.

Epidemiological Mathematical Model SIR

We adopted the SIR Mathematical Model as a tool for monitoring the epidemiological situation in the state of the Tocantins, whose first insertions of this model in epidemiology were in 1927, by Kermack and McKendrick (KEELING; ROHANI, 2008; KERMACK; MCKENDRICK, 1927; KRETZSCHMAR; WALLINGA, 2009) in order to make predictions and qualitative analysis of the spread of infectious diseases in humans. More recently, in 2013, this model was systematically improved by Isea and Lonngren (ISEA, 2013). This model is known as the SIR model in reference to susceptible, infected, and removed individuals from a certain population. This model consists of dividing the population into disjunct classes of people, denoted as follows:

$S:=$ Number of susceptible to contagion;
$I:=$ Number of Infected (people who infect);
$R:=$ Number of people removed (recovered and killed);
$N:=$ Total number of people in the population.

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This model aims to understand the dynamics with which individuals move from one class to another and the impacts that this can cause on a given population.

Probability of contagion of a population

The likelihood of contagion is a number that depends on the time of exposure between the infected individual and the susceptible individual. With that, we introduce the term $\beta\, dt$ where dt represents variation in contact time and β the probability of contagion per unit time. The $\beta\, dt$ factor is the probability of contagion between two individuals, one being infected and the other susceptible. In this case, β it is called transmissibility.

In certain scenarios, for example, on a crowded collective bus, we do not know who the infected people are and who are susceptible. However, we can determine the likelihood of being in front of an infected person. In this sense, the probability is given by the $\frac{I}{N}$, ratio, which is the classic way of defining probabilities, that is, the favorable cases, divided by the possible cases.

Therefore, let us denote by c the average number of contacts that an individual makes in a given time interval with infected people. Then, by multiplying the factors β dt, c and $\frac{I}{N}$ we obtain the probability of contagion of an individual: $c\beta(I/N)dt$. In summary, a susceptible person has probability of infection a $c\beta(I/N)dt$ when exposed to infected people over a period of time dt.

Deducing model equations

The SIR model is characterized by a triple of differential equations that make approximate predictions with a view to real situations of how a given disease spreads over time. The differential equations are in the unknowns S, I, and R. We then proceed, in an intuitive way, to deduce the model equations. We emphasize that we will not do a mathematical treatment of the equations here regarding the existence and uniqueness of solutions, asymptotic behavior of solutions and dependence on initial conditions.

Initially we will deduct the equation for S. Thus, let dS be the rate of change of susceptible people in time dt. So, the $Sc\beta(I/N)dt$ number is the total probability of people susceptible to being infected in time dt. Therefore, the set of susceptible people S loses the amount $Sc\beta(I/N)dt$ in the time variation dt. Thus, $S = -c\beta(I/N)S\, dt$. As a result, we have the differential equation in S: $\frac{dS}{dt} = -\frac{\beta cI}{N}S$.

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Now, we proceed in a similar way to obtain equation I. Let us note that in a time variation dt, the variation of d, dI, will absorb those people who were susceptible and contaminated, namely, $c\beta(I/N)S\ dt$. In this same variation of time, dI, you will lose the variation of individuals who recovered or died, dR. With that, we obtain the second equation of the model: $\frac{dI}{dt} = \frac{\beta cI}{N}S - \frac{dR}{dt}$.

We will denote by γ the rate of removal of an individual in a given period of time. Thus the number $\gamma I\ dt$ is the total number of individuals removed at time dt. With that, we arrive at the third equation of the SIR model: $\frac{dR}{dt} = \gamma I$.

Substituting the above equation in the equation as a function of $\frac{dI}{dt} =$ we obtain: $\frac{dI}{dt} = \frac{\beta cI}{N}S - \gamma I$.

These three equations make up the SIR model. Some modifications are made to this model to obtain increasingly accurate interpretations of reality. However, since our objective is to present the model indications in a didactic way, we will omit such modifications. In summary, mathematically, we have the following system of equations:

$$\begin{cases} \dfrac{dS}{dt} = -\dfrac{\beta cI}{N}S \\ \dfrac{dI}{dt} = \dfrac{\beta cI}{N}S - \gamma I \\ \dfrac{dR}{dt} = \gamma I. \end{cases}$$

In addition to understanding the dynamics of contagion, we need to understand the impact on the health network. For this, supposing the system of equations to be solved, we will consider $D = \sigma I,\ H = \theta I\ e\ U = \tau I$, where D represents the number of infected people who die with rate σ; H is the number of infected people who need hospitalization with rate θ and U the number of infected people who need Intensive Care Unit (ICU) whose rate is represented by τ.

Some qualitative interpretations of the model

In this section we will analyze the first two equations. Remember that the unknowns S, I and R are related by $S + I + R = N$. To simplify the model, we will make the following change of variables over time: t↦ (1 / βc) u. Then $\frac{dS}{dt} = \beta c\frac{dS}{du}$. With that, we can rewrite the first equation of the model as: $\frac{dS}{du} = -\frac{I}{N}S$.

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In other words, by rescheduling time, we obtain a very simplified equation, however, it offers us the conditions to get closer and closer to reality. From the equation $\frac{dS}{du} = -\frac{I}{N}S$, we see that $\frac{dS}{du} < 0$, since $I(u), S(u)$ and N are positive numbers for any values of u. Therefore, the number of susceptible people will decrease over time. That is, people will leave the class of the susceptible and will enter the class of infected people at some point.

We will analyze the behavior of function $I(u)$, that is, the behavior of the number of infected people over time. We have, after changing variables as presented above:

$$\frac{dI}{du} = \frac{I}{N}S - \frac{\gamma}{\beta c}I = \left(\frac{S}{N} - \frac{\gamma}{\beta c}\right)I.$$

If $\gamma/(\beta c) < S/N$, then, as $I(u), S(u)$ and N are positive numbers for any values of u, $I(u)$ is an increasing function and therefore the number of infected people will increase over time caused by an epidemic.

If $\gamma/(\beta c) > S/N$, then, as $I(u), S(u)$ and N are positive numbers for any values of u, $I(u)$ is a decreasing function, which means that the number of people infected it will decrease over time and, consequently, there is the possibility of controlling the disease. Thus, in order to be able to deal with the increase in the number of infected, in order to stop the spread of contagion, we must control the parameters γ, β and c well.

If $\gamma/(\beta c) = S/N$, then $I(u)$ is a constant function. This means that the number of infected remains constant.

The classic mathematical facts that allow us to make these conclusions are:

a) a negative derivative function is decreasing;

b) a function with a positive derivative is increasing;

c) a function with a null derivative is constant.

An interpretation of the argument presented above is that individuals will leave the compartment of susceptible people and will enter the class of infected people and after some time they will enter the compartment/class of those removed.

A number that plays an important role in understanding epidemiological behavior is the number $R_0 = \frac{\beta c}{\gamma}$. The same is called reproduction factor or reproduction number.

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We are now in a position to translate the mathematical information discussed above into epidemiological language:

- If the individual's rate of contagion is greater than the rate at which he recovers or dies, that is, $\beta c > \gamma$, then $R_0 > 1$ thus implying that we have no control over the number of people infected, causing an epidemic.
- If the individual's rate of contagion is less than the rate at which he recovers or dies, that is, $\beta c < \gamma$, then $R_0 < 1$ implying that we have the possibility of controlling the number of infected people.
- If $R_0 = 1$ then we have an epidemic equilibrium condition or epidemic threshold.

These are the main conclusions of the SIR model. To consider the spread of a disease caused by an infectious agent, the loss or factor βc in relation to factor γ, or to force an approximation between the two factors that affect the epidemic effect.

For this to happen, reduce the β, transmissibility, through the adoption of protective measures through the use of masks, gloves, constant hygiene, for example. We must also reduce the average contact rates c, and this can be done through restrictive measures, such as quarantine, social distance or other means of containment. Allied to these measures, the removal factor γ should increase, and this can be done through the use of medicines and vaccination of the population. However, a vaccine or an effective treatment against the new coronavirus has not yet been found or further strengthening as epidemiological guidelines from health agencies. For more details suggested (KRETZSCHMAR; WALLINGA, 2009), (TODA, 2020).

How do we do it? As we clearly select below, social distance is a first solution so that we can have some control over the speed at which the disease spreads.

Discretization of equations

The discretization process that we will adopt here consists of allowing the time variable f to cover only the set of natural numbers. With that, we can think of time as day, hour, minutes, etc. In this case, we make the following adjustments: If f is a function of t, then when we do $t = n$, we use the notation $f(n) = f_n$ for the image of the function f and $df_n = \Delta f_n = f_{n+1} - f_n$ for changing the function from time n to time $n + 1$. So, we can rewrite the system of equations that make up the SIR model as:

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$$\begin{cases} \Delta S_n = -\dfrac{\beta c I_n}{N} S_n \\ \Delta I_n = \dfrac{\beta c I_n}{N} S_n - \gamma I_n \\ \Delta R_n = \gamma I_n. \end{cases}$$

Or equivalently:

$$\begin{cases} S_{n+1} = S_n - \dfrac{\beta c I_n}{N} S_n \\ I_{n+1} = I_n + \dfrac{\beta c I_n}{N} S_n - \gamma I_n \\ R_{n+1} = R_n + \gamma I_n. \end{cases}$$

The new equations that emerge from this process are called finite difference equations or recurring equations. Thus, with the interpretation of this type of modeling, it is possible to know the data of a given phenomenon at time n, so we can predict how that phenomenon behaves at the next time $n + 1$. In addition, we can, based on previously available data, make projections of the long-term spread of the disease and use LibreOffice Calc spreadsheets. (KRETZSCHMAR; WALLINGA, 2009).

Application of the SIR model to Covid-19 in State of the Tocantins

One of the great difficulties that scientists have been facing in relation to Covid-19, is the lack of data and precise parameters. For this reason, we will use the parameters available in the works (MOSSONG, 2008), (ROCKLÖV, 2020). It following these authors, we will take $c = 13.4$, $\beta = 2\%$ and $\gamma = 0.1$. The value $\gamma = 0.1$ means that the average removal time is 10 days. We also considered, $\sigma = 0.9\%$, the mortality rate, $\theta = 13.80\%$, the proportion of those infected who need hospitalization, and $\tau = 4.70\%$, the proportion of those infected who need ICU care.

When considering a hypothetical scenario, in which no measures of social isolation or protection measures are taken, the SIR model would behave according to the situation described in Figure 2, below.

Figure 2 Simulation of the SIR model without restriction measures.

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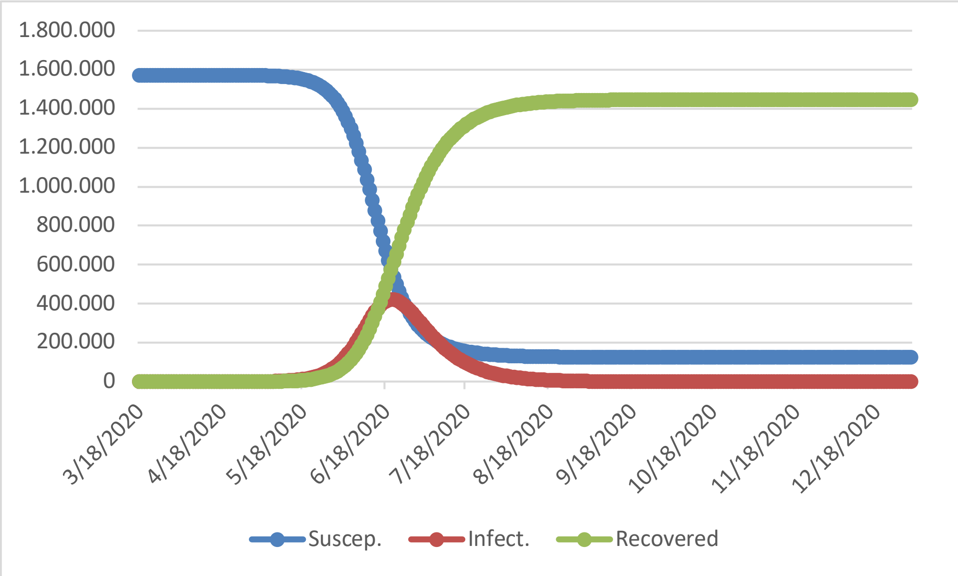
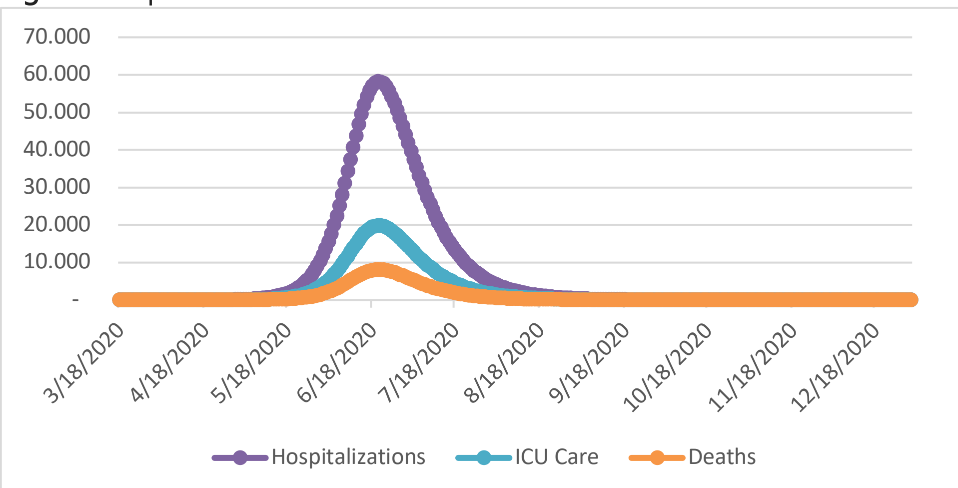


Source: research authors.

As we can see in Figure 2, when considering the case of the Tocantins, whose first confirmed case occurred on March 18, 2020, the pandemic would reach the peak of the accumulated contagion curve on June 18 this year, with approximately 421 thousand people infected. On the other hand, the first wave of contagion would end around the 18th of August of the same year.

Figure 3 impact on the health network.



Source: research authors.

Figure 3 shows that during the peak of the epidemic, the number of people hospitalized could be close to 60 thousand. The number of people who would need an ICU, in this context, is approximately 20 thousand. These 80 thousand people needing hospital beds, considering that the health network provided some around 2 thousand,

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would lead to a catastrophic scenario, collapsing the state's health system (TOCANTINS, 2020b). The funeral service would also be hit, since at the peak of the epidemic we could have up to 3975 deaths.

The entire situation predicted by the model suggests that measures be taken in the sense that people should not contract the infection at an increasing rate or at the same time. It means that the measures to be taken must need to ensure that the peak of the contagion curve is below the service capacity of the health network and thus contributes to the flattening of the contagion curve, which according to the model it is descript by R close to 1.

Thus, to guarantee the health security of the population of Tocantins, from March 18 to May 16, the state authorities, under the guidance of the own committee to confront COVID-19, recommended increased social distance, as a measure of containment of the disease progression.

Social detachment and pandemic (no-)evolution

In this section, we make a thorough analysis of social distance in the Tocantins and its relationship with the evolution of the pandemic. More precisely, we investigate the impact of measures such as the lockdown on the rate slowing the spread of the virus.

Figure 4, below, shows the behavior of the social isolation index in the state from February 1st to June 10th, data available in (INLOCO, 2020). To this end, we are interested in five specific periods: from 03/13 (date when the first cases were notified in the state) to 03/29 (deadline when the isolation index tended to grow); from 03/30 (date when the downward trend starts) to 05/15 (deadline before the lockdown is in effect); from 5/16 (start of lockdown) to 5/24 (end of lockdown); 05/25 to 06/10 (remaining period); from 03/30 to 06/10 period since the beginning of the decay trend.

Figure 4 Social isolation index.

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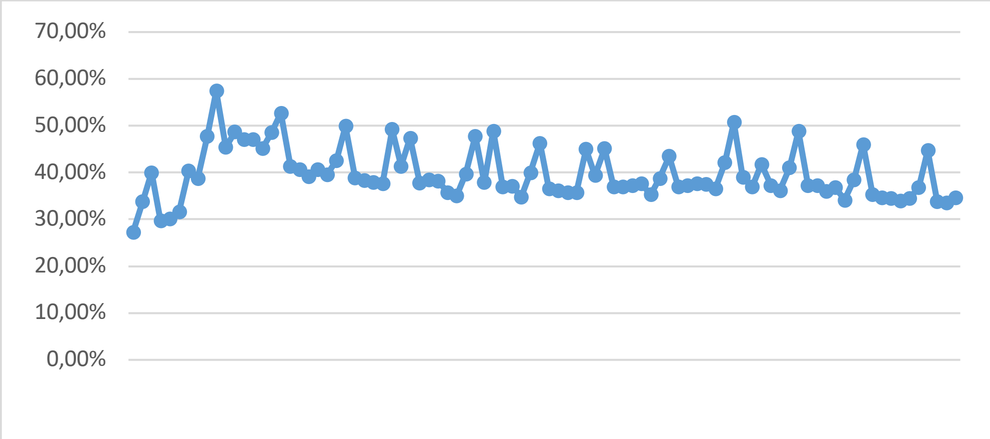
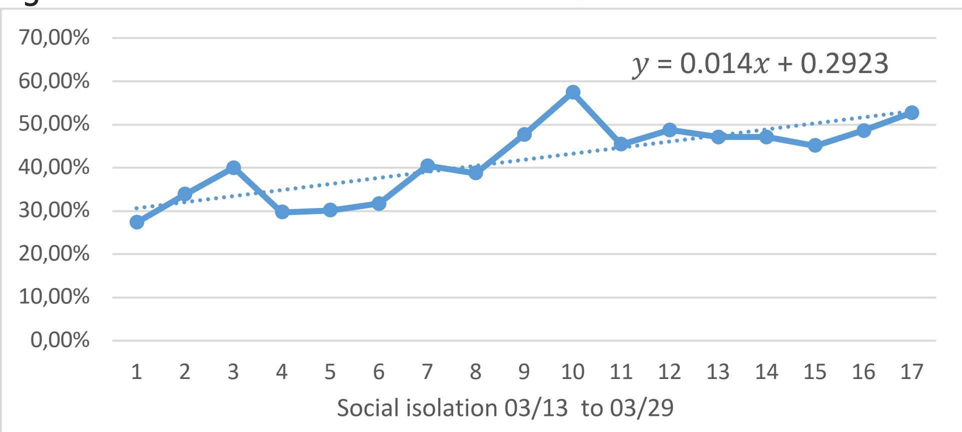


Source: research authors.

03/13 to 03/29. This period includes the beginning of notifications of the first cases and the cut-off date for the growing trend of social isolation. This can be seen in Figure 5, where the growth rate is 0.014, and the isolation average is 41.85%. As we will see later, this period of growth in social isolation has a strong influence in decreasing the reproductive factor of the pandemic, which is very relevant for the control of the disease.

Figure 5 Social isolation index and trend line.



Source: research authors.

03/30 to 05/15. As of 03/30, the social isolation index has a decreasing trend, that is, on average, isolation is declining. The decay rate is -0.0009 and the average insulation is 39.69%. As a result, there was a decrease of 5.16% on average and compared to the previous period. Figure 6, below, illustrates the trend line and the behavior of the social isolation index.

Figure 6 Social isolation index and trend line.

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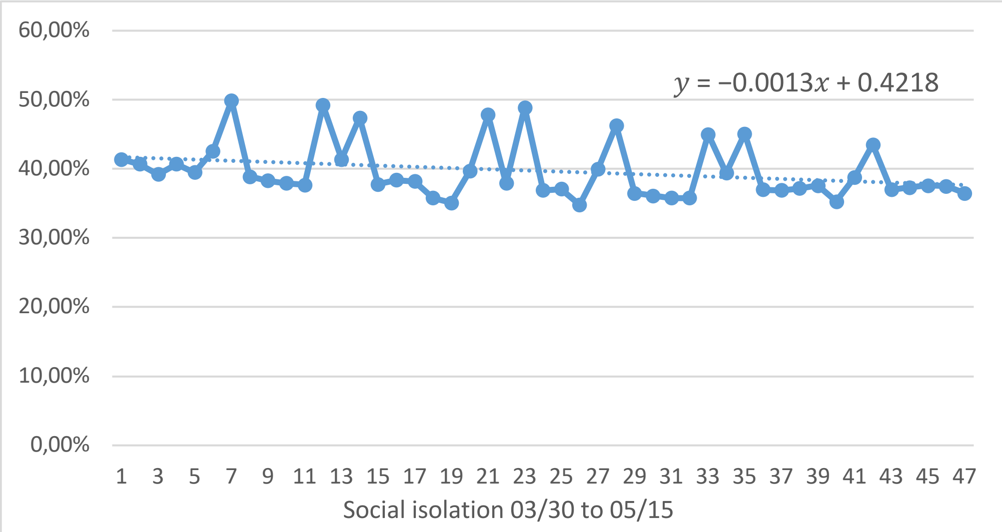
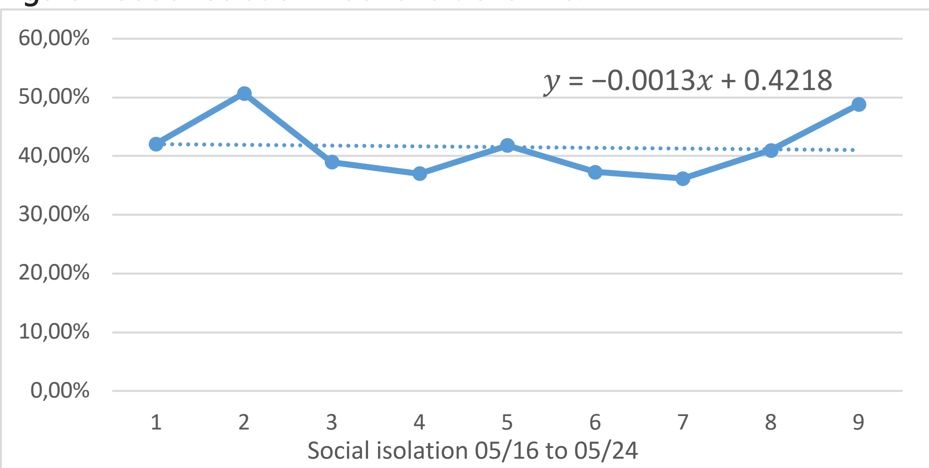


Source: research authors.

5/16 to 5/24. This was the period in which the lockdown was in force in the cities with the highest incidence of cases in the state according to decree no. 6093. Even with this more restrictive measure, the trend of isolation is still decreasing with a rate of -0.0013 and the average in the period is 41.54%. Note that there was an increase of 4.67% over the previous period. Note also that, concerning the previous period, the coefficient or rate of decrease goes from $-0{,}0009$ to -0.0013. This means that the rate of decline in the social isolation index decreased by 30.76% compared to the rate of decrease in the previous period. As shown in Figure 7, below.

Figure 7 Social isolation index and trend line.



Source: research authors.

5/25 to 6/10. As of 05/25, the state left the lockdown and returned to the extended social distance. In this period, we have a linear downward trend with a rate of -0.0012.

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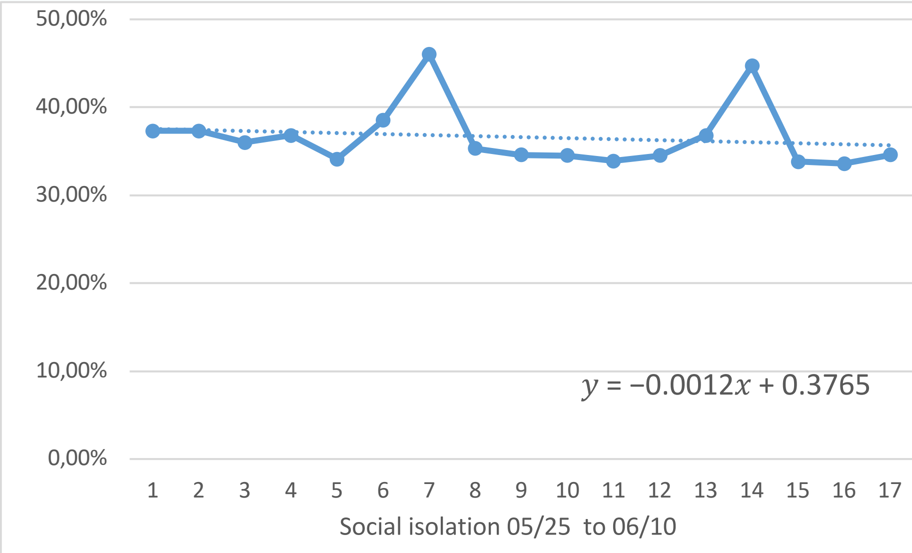
Since $-0.0012 > -0.0013$, then the decay speed of social isolation increased compared to the previous period. The increase was 7.69%. The average social isolation index in this period is 36.61%, which means that we had a drop of 11.88% concerning the previous period, which can be seen in Figure 8, below.

Figure 8 Social isolation index and trend line.



Source: research authors.

3/30 to 6/10. This comprises the entire period of decay in the social isolation index. As we saw above, from 03/30 to 05/15, the decay rate was $-0{,}0009$. This means that, if nothing was done, this trend could last until 06/10, making the index of social isolation reach even more worrying numbers, given that the ideal in times of pandemic is a number between 60% and 70%. However, as we can see in Figure 9 below, the trendline rate from 03/30 to 06/10 is $-0{,}0006$. This means that the lockdown caused a reduction of 33.33% in absolute value in the decay rate of social isolation in the mentioned period. The average for the period is 39.20% which is approximately the average for the period from 03/30 to 05/15.

Figure 9 Social isolation index and trend line.

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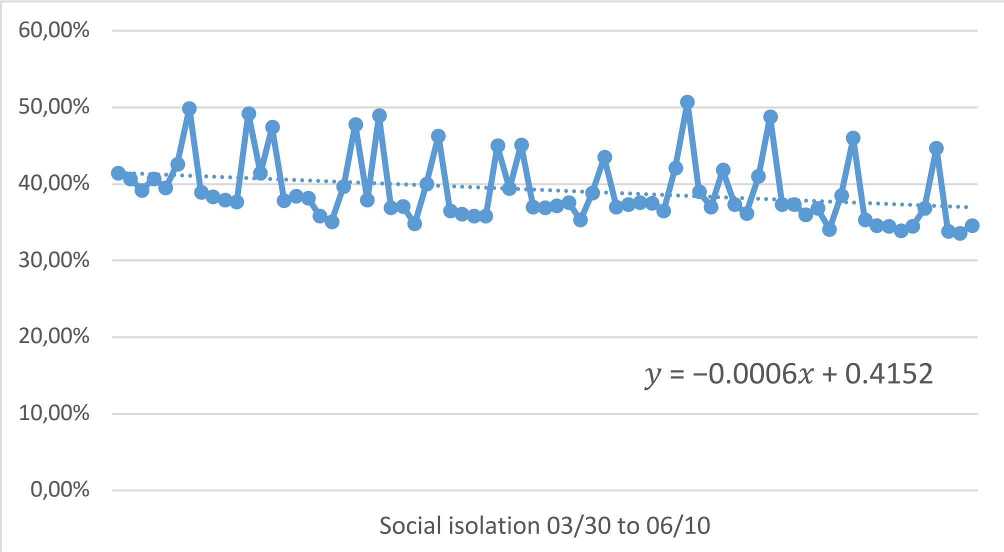

Source: research authors.

Reproduction Factor

When exploring the relationship between the social isolation index and the average contact rate, and consequently with the reproduction factor R_0. It follows from the deductions of the SIR model, that R_0 plays an important element to be highlighted in the study of epidemics. The following describes the behavior of the reproduction fact from March 18 to May 29. This is done using the formula $R_0 = (c\beta)/\gamma$, as follows. We set the values of β, which is the transmissibility of the virus, γ the inverse of the removal time. Having done this, we used the available data on infected people, and solving the equations for the day in question, we found the value c, the average rate of daily contact. Thus, we can calculate the value of R_0 daily.

Based on the period mentioned, we solve the system each day and plot the graph of the daily reproduction factor values and the trend line. This is plotted in Figure 10, below. In this time interval, the average reproduction factor was 3.47.

Figure 10 Reproduction factor and trend line.

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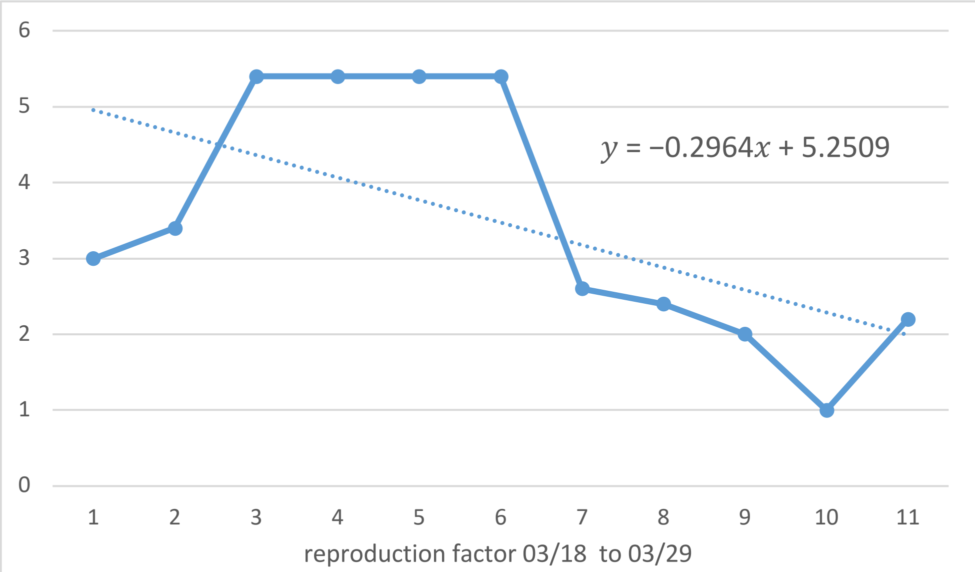

Source: research authors.

Note that the trend line is decreasing, while in the same period the index of social isolation has an increasing trend. This confirms the intuition that the disease's reproduction factor is inversely proportional to the social isolation index.

Now let's look at the reproduction factor in the period from 03/30 to 05/15. Figure 11, below, shows the behavior of the production factor and the trend line. Note that the trend line is increasing at a rate of 0.0276. Note that in the same period the trend of the social isolation index is decreasing, indicating that as the social distance decreases the number of reproduction increases. Note that if in the previous period the reproduction factor approached 1 while social isolation increased, already in this period the reproduction factor moves away from 1, with an increasing trend, as a consequence of the decrease in social isolation. Even so, given that the growth rate of the social isolation index is low, the average reproduction factor was 2.08 which is still high.

Figure 11 Reproduction factor and trend line.

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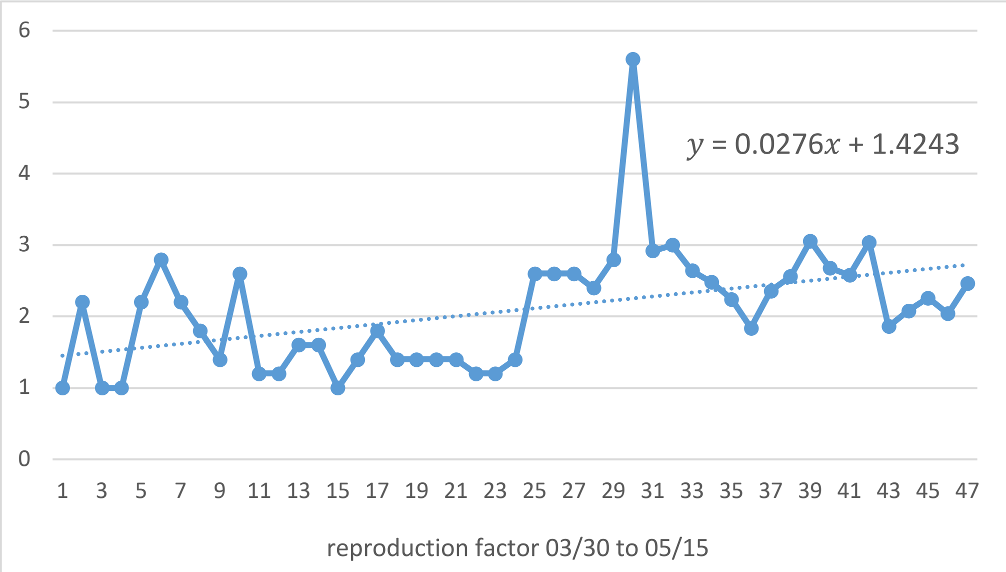
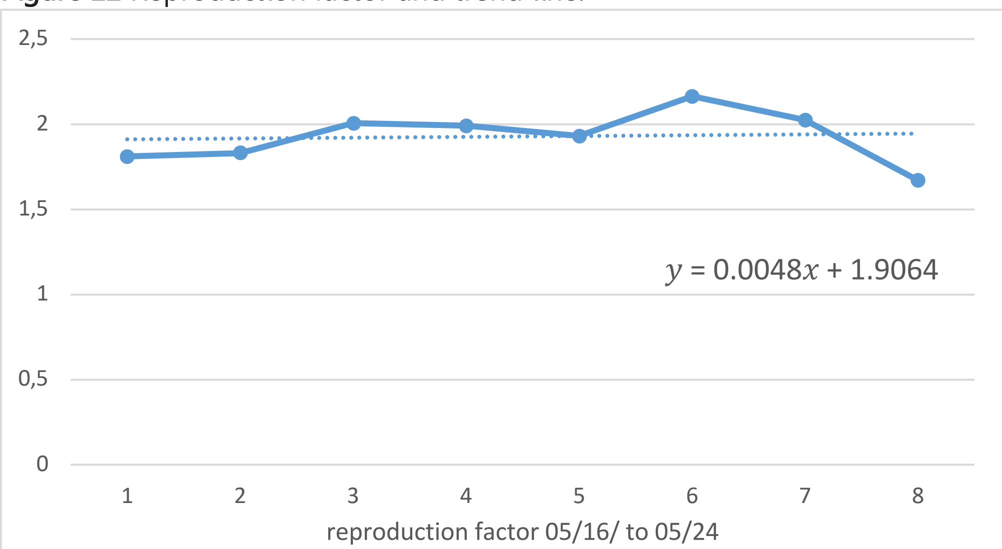


Source: research authors.

Figure 12, below, shows the behavior of the reproduction factor during the lockdown, that is, from 5/16 to 5/24. See that the restrictions imposed by the government impacted a slowdown in the growth of the trend line. In other words, the 0.0276 rate before the lockdown fell by 82.6%. The average of the R_0 values in this time interval was 1.92, which means that it had a decrease of 7.69%. Although it has decreased compared to the previous period, this average is still quite high. Remember that to be able to control the pandemic, it is necessary that R_0 stays and remains less than (or the closest) to 1. We also noticed that in this period, social isolation tended to decrease.

Figure 12 Reproduction factor and trend line.



Source: research authors.

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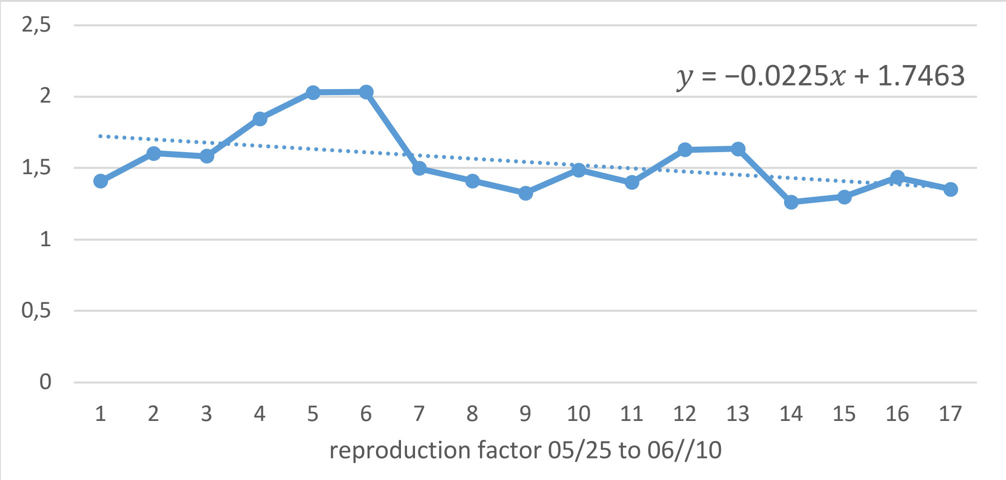
Now we move on to the period from 05/25 to 06/10. In this period, the social isolation trend line had an almost zero rate of decrease. However, as we can see in Figure 13, below, the reproduction factor has a negative trend with a rate of -0.0225. This indicates that, even with the low insulation index, safety measures such as wearing a mask, constant hand washing, played an important role in the R_0 calculation. The average in this period was 1.54 considering two decimal places.

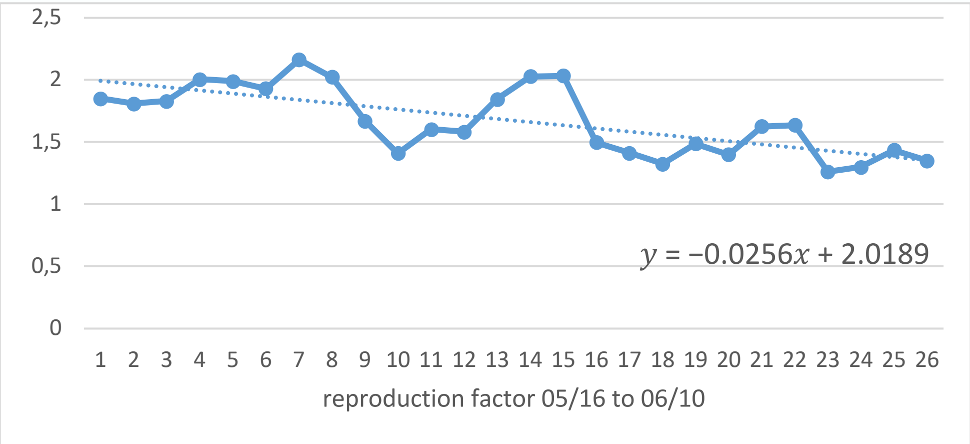
Figure 13 Trendline reproduction factor.



Source: research authors.

One way to make a short and medium-term forecast is to look at the trend line of the daily reproduction factor values. Note that this line, dotted straight in Figure 14, is given by $y = -0.0256x + 2.0189$. Then, we take $R_0(x) = -0.0256x + 2.0189 + (-1)^x sen(1/x)$ which is a good approximation for y.

Figure 14 Reproduction factor and trend line.



Source: research authors.

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Therefore, we can build Table 1, below, with estimates for R_0depending on the day, from the date of 06/11 to 21/06.

Table 1 Estimates for R_0.

x	Data	$R_0(x)$
26	06/11	1.3917
27	06/12	1.2906
28	06/13	1.33780
29	06/14	1.2420
30	06/15	1.2842
31	06/16	1.1930
32	06/17	1.2309
33	06/18	1.4438
34	06/19	1.1779
35	06/20	1.0943
36	06/21	1.1250

Source: research authors.

Therefore, based on R_0, generated in Table 1, above, we can plot, on the same graph, the cases of infected persons reported by the state health department and the infected data generated by the model, as can be seen in Figure 15, Next. The indication is that if the reproduction factor continues, even if it fluctuates, tending to become less than 1 over the course of days, then the number of contagions of the disease will decay. Otherwise, the equivalent of this about the actions of the public authorities is to ensure that the index of social isolation and hygiene measures that will prevent contagion, remains constant or increasing over time.

The interpretation of the model, in this configuration considering the time interval 03/18 to 06/21, is that the new peak was translated which means that the contagion curve was flattened. It is observed that, without restriction measures, the number of contaminated at the peak of infection would be around 421 thousand people, while, when adopting the restriction measures as indicated by the model, this number was reduced to a number close to 8.1 thousand infected. This relieves the health network in addition to saving lives.

Figure 15 SIR model without susceptibles.

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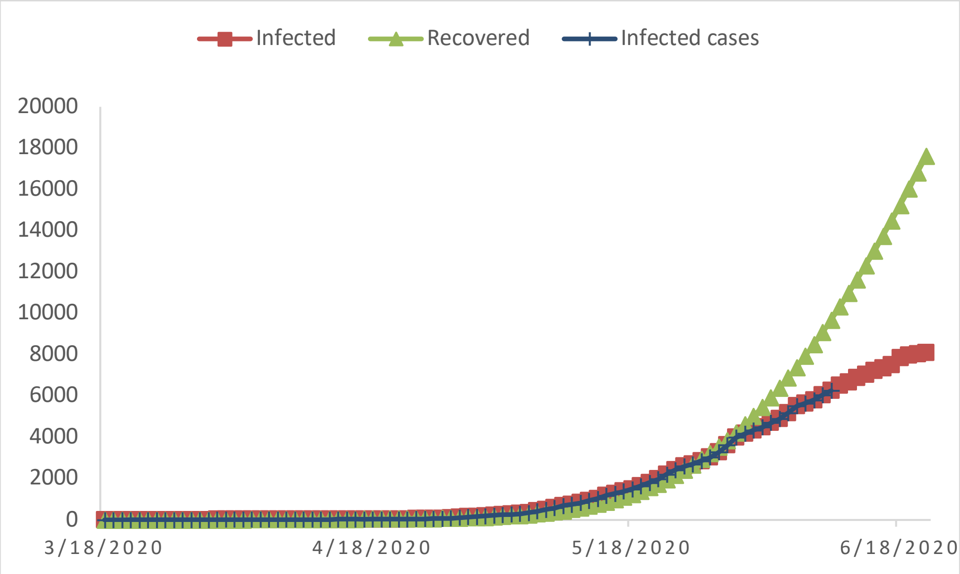
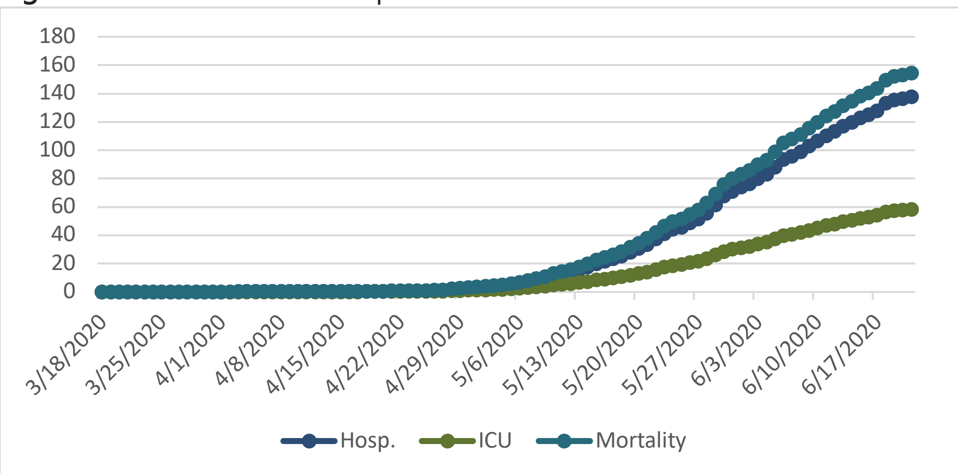


Source: research authors.

The effects of social distance measures on the health system can be seen in Figure 16, below. With the reduced number of people being infected at the same time, we can see that until June 10, the last data collection date, the health system in the state did not collapse, being able to attend to the new cases that arose needing hospitalization. and ICU services. On this date, 107 people out of the 6257 tested positive, cumulative number, used hospital services, which represents 1.71% of the accumulated confirmed cases. The number of people in the ICU reached 45, which represents 0.72% of the accumulated confirmed cases. The number of accumulated deaths was 120, representing 1.92% of the total cases, (TOCANTINS, 2020a).

Figure 16 Evolution of the impact on the health network.



Source: research authors.

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Conclusion

The present study analyzed the impact on the health network in the state of Tocantins, resulting from the Covid-19 pandemic, caused by the new coronavirus (SARS-CoV-2), based on the application of the epidemiological mathematical model SIR. The model's simulations indicated situations similar to the reality faced by the state, thus making it possible to guide state and municipal managers in decision making to guarantee health and biosafety conditions to the population.

Initially, the measures of containment and sanitary barriers, imposed by the government, were sufficient to contain the increase in the rate of contamination. However, some cities have reached high levels of contagion by saturating the health network in health regions such as the Middle North Araguaia and Bico do Papagaio, thus compromising the results expected by the strategies for coping with the disease.

As we have seen, the reproduction factor R_0 is inversely proportional to the social isolation index. This means that as the insulation rate drops, the contagion force increases. It was also observed that the social isolation index from May 1st until June 10th, had a sharp drop, averaging close to 38.49% while the ideal value indicated is a number between 60% and 70%. This indicates that if the index continues in this trend (decreasing), R_0will deviate on average from the value 1, implying the explosive appearance of new cases and with this the acceleration of contagion, which can cause the collapse of the health system.

Even though the SIR mathematical model offers conditions for monitoring the epidemic situation in the state of Tocantins, the strong call for the premature opening of trade and the easing of the rules of social distance can cause an accelerated increase in new cases, giving rise to the second wave of contagion. Therefore, what is indicated is that great care must be taken by adopting safe measures of protection and detachment so that the fall in the social isolation index is not abrupt or even more accentuated concerning the trend already observed.

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RESUMO:
Esse artigo é um estudo acerca do comportamento e propagação da pandemia de COVID-19, no estado do Tocantins, a partir dos dados notificados no período de 18 de março a 10 de junho. Para tanto, utilizou-se uma modificação do modelo matemático SIR, no qual foram acrescentados alguns compartimentos auxiliares. Analisamos aspectos epidêmicos tal como a velocidade da curva de contágio e seus impactos no sistema de saúde. Como os dados são disponibilizados diariamente, foi realizada uma discretização do sistema de equações diferenciais que compõem o modelo e a partir da disponibilidade dos dados conhecidos investigamos a correlação entre o índice de isolamento social e o fator de reprodução básico. Através de uma interpolação bastante simples obteve-se taxas de contágio aproximadas propiciando avaliar o comportamento da evolução das curvas de contágio e daquelas que dependem delas, o que nos possibilita antecipar cenários com base nas linhas de tendência dos dados gerados auxiliando assim as tomadas de decisões do poder público.

PALAVRAS-CHAVE: COVID-19; Modelo matemático SIR; Índice de isolamento social; Estado do Tocantins.

RESUMEN:
Este artículo es un estudio sobre el comportamiento y la propagación de la pandemia de Covid-19, en el estado de Tocantins, basado en datos reportados del 18 de marzo al 10 de junio. Se utilizó una modificación del modelo matemático SIR, en el que se agregaron algunos compartimentos. Analizamos aspectos epidémicos como: la carga sobre el sistema de salud; ralentizar la curva de contagio o aplanar la curva. A medida que los datos se ponen a disposición diariamente, se realizó una discretización del sistema de ecuaciones diferenciales que componen el modelo en función de la disponibilidad de datos conocidos, con los que se generaron las tasas iniciales. Mediante una interpolación muy simple, se obtuvieron tasas de contagio aproximadas, lo que nos permitió evaluar el comportamiento de la evolución de las curvas de contagio y las que dependen de ellas, lo que nos permite anticipar escenarios basados en las líneas de tendencia de los datos generados, lo que ayuda a la toma de decisiones del poder público.

PALABRAS-CLAVES: COVID-19; Modelo matemático SIR; Índice de aislamiento social; Estado de Tocantins.

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