GIMA
Geographical Information Management and Applications

Modelling governmental risk perception and coping appraisal during the COVID-19 pandemic in the Netherlands

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GIMA MSc. Thesis
May 2021
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May 2021
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ACKNOWLEDGEMENTS

I would first like to thank my supervisor, Ellen-Wien Augustijn-Beckers. With your expertise, you helped me to set up this wonderful research. At times when I lost the focus on what was important for my research, you helped me get back on the right tracks by sharpening my thinking again during our discussions and with your feedback. I would also like to thank Carmen Antonj, my second supervisor, who helped me with her background in medical geography with refining my research and obtaining new ideas. I greatly appreciate that you took the time to help me besides your PhD. For both of you: your insightful feedback and fantastic guidance has been much appreciated and it brought my work to the next level!

In addition, I would like to thank my mother for her support during my thesis. I also would like to thank my friends for encouraging me during this process and giving me good advice based on their own thesis experiences. And last but not least, I would like to thank Sander for his awesome encouragements, his interest in my subject and for providing me help when I needed it. I really enjoyed working from home together during such unusual times.

SUMMARY

The novel coronavirus 2019 (SARS-CoV-2) is a highly infectious virus that started in December 2019 in Wuhan, China, and caused the disease COVID-19. It has since then rapidly spread across the globe. On 27 February 2020, the first person in the Netherlands was diagnosed with COVID-19, and on 23 March 2020, measures were taken by the Rutte III cabinet, which resulted in an ‘intelligent lockdown’, a lighter version of a full lock-down. Since vaccines were not yet available in 2020, the virus had to be controlled by measures taken by the government, such as social distancing, quarantine, isolation, or community containment.

Models can be very useful in evaluating the effectiveness of these measures and in predicting the expected results of different combinations of interventions. For this purpose, models are needed to simulate the spread of the disease, the interventions a government can take, and the country's response. The risk perceived by the government and subsequent interventions are two steps in the decision-making process of the Protection Motivation Theory (PMT). PMT divides the process into two steps: risk assessment (risk perception) and coping appraisal. Based on these two steps, different interventions scenarios can be evaluated.

For the simulation of the COVID-19 outbreak in the Netherlands, a pertussis model was converted into a COVID-19 model. In the model, three scenarios were created: the Roadmap scenario, the economic scenario and the age scenario. The Roadmap scenario is based on the “Routekaart” the Dutch government set up to identify when to implement measures. In the economic scenario, the order of measure implementation depends on the economic impact of the measures. And in the age scenario, measures are ordered based on their effect on the number of infections in one of nine age groups and implemented once the number of infected individuals in the different age groups reaches a certain risk level.

Prior to the creation of the scenarios, the outbreak of COVID-19 in the Netherlands in 2020 is stimulated to test the base model by implementing predefined lockdowns. Eventually, the model is run without any measures, with predefined lockdowns, with the Roadmap scenario, with the economic scenario and with the age scenario.

The model was calibrated using available COVID-19 data, travel data and a survey. The calibration was made challenging since many variables and risk factors are still unknown, undocumented or unspecified.

According to the model, predefined lockdowns and the three scenarios have a similar effect on the number of infected individuals and hospitalizations. But, by looking at the periods the measures need to be implemented, the age and economic scenario are both more attractive ways to implement measures as the duration of the measures are shorter. In the model, the measures fluctuate a lot, which would mean that the government would need to change the measures every day. This does not seem to be realistic as the changes in measures would work counterproductively, as changing the measures often could cause confusion, dismay and unwillingness among the population. Furthermore, which scenario is better also depends on the priorities of the government in terms of the impact of the measures on the age groups within the Netherlands and economy.

The model of this thesis contributes to a better understanding of risk perception and coping appraisal of the Dutch government during a pandemic. Even though the model did not possess all initially planned functionalities, a lot of information can be derived on the impact of different measures from the outcomes. Forasmuch as the virus is relatively new, just like the COVID-19 literature itself, research about risk perception and coping appraisal together with the spatial diffusion of the virus is limited. There is thus much potential in future research about risk perception and coping appraisal with a geographical component.

GLOSSARY

Case fatality ratio (CFR)	Represents the deceased among identified and confirmed cases (Hauser et al., 2020).
Coefficient of variation	The ratio of standard deviation to the mean (Lorscheid et al., 2012). Is used to check the stability of a simulation model.
Coping appraisal	During the coping appraisal, an individual (in this thesis: the government) decides how to respond.
Coronavirus	Causes the Coronavirus disease (COVID-19), a highly infectious disease.
COVID-19	The virus, SARS-CoV-2, is the cause of Corona Virus Disease (COVID-19), which can cause symptoms like coughing, shortness of breath and fevers (Lai et al., 2020; Xu et al., 2020).
Epidemic	A widespread occurrence of an infectious disease in a community
Gathering and event travelling (GAET)	Gathering and event travelling is defined as the travelling for recreational activities of at least one hour that are undertaken outside an individual's home municipality.
Herd immunity	Population immunity achieved through previous infection or vaccination of the individuals in the population (World Health Organization, 2021).
Holiday travelling	An individual's movement to a place away from home for an extended period for leisure and recreation.
Infection fatality rate (IFR)	A ratio, which represents the number of deceased among all infected. This includes undiagnosed infected individuals (Hauser et al., 2020).
Infectious period	The infectious period is the period in which an infected individual is capable of transmitting the virus directly or indirectly to another individual.
Incidence	The occurrence, rate, or frequency of a disease.
Incubation period	The incubation period is the number of days between when you are infected and when you have symptoms (Lauer et al., 2020).
Immunity	The duration of COVID-19 immunity is the time the human body can protect itself against the virus.
Job commuting	Daily movements of people going to work (Tjalma, 2016).
Lockdown	Nationwide physical distancing measures and movement restrictions (World Health Organization, 2021) that are meant to reduce the contact between individuals
Netlogo	An integrated development environment (IDE) for agent-based modelling. It uses its programming language (*NetLogo*, 2020).
Pandemic	An epidemic worldwide or over a very large area
Pertussis	Whooping cough, a highly contagious respiratory tract infection.
Quarantine	A period of isolation in which people that have been exposed to a virus are placed.
Reproduction number (R number)	Is the average number of people a COVID-19 case infects and also called the R_0 (van den Driessche & Watmough, 2008).
SARS-CoV-2	The virus, SARS-CoV-2, is the cause of Corona Virus Disease (COVID-19), which can cause symptoms like coughing, shortness of breath and fevers (Lai et al., 2020; Xu et al., 2020).
Serial interval	The serial interval is the time between the primary case showing symptoms (the infector) and the secondary case (the infected) showing symptoms (Rai et al., 2020).
School commuting	daily movements of people going to school (Tjalma, 2016).
Threat appraisal	During the threat appraisal, the potentiality and the level of a threat are assessed. This is also called risk perception.
Visit travelling (VT)	The travelling by an individual to friends or family members in another municipality (i.e. not their home-municipality) (own definition).

TABLE OF CONTENTS

Acknowledgements 2
Summary 3
Glossary 4
1. Introduction 8
1.1 Research questions 11
1.2 The scope of the research 11
2. Theoretical Background 13
2.1 COVID-19: Worldwide 13
2.2 COVID-19: Research 14
2.2.1 Symptoms 14
2.2.2 Measuring Transmission 14
2.2.3 Measuring Spatial Spread 16
2.2.4 COVID-19 prevention 16
2.2.5 COVID-19 and different population groups 17
2.2.6 Similar viruses 18
2.2.7 Seasonality 19
2.3 COVID-19: The Netherlands 19
2.4 Protection motivation theory 21
2.4.1 Threat appraisal 21
2.4.2 Coping appraisal 22
2.5 Agent-based modelling 22
2.5.1 Agents 23
2.5.2 Agent relationships 23
2.5.3 Agents' environment 23
2.5.4 ABM example 1: Bayesian networks for spatial learning 24
2.5.5 ABM example 2: Spread of pertussis and vaccination 25
3. Methodology 27
3.1 Literature and data analysis 27
3.1.1 Theoretical background 28
3.1.2 Software 28
3.1.3 Geographical data 28
3.1.4 Population data 29
3.1.5 Commuter data 30
3.1.6 Travel data 30
3.1.7 Contact matrix 33
3.1.8 COVID-19 data 34
3.1.9 Risk perception and coping appraisal data 35
3.1.10 Source data 37
3.2 Conceptual model & implementing variables 39
3.2.1 Updating existing model 39
3.2.2 Conceptual model 39
3.2.3 Population model 40
3.2.4 Rule-based sub-model 42
3.3 Verifying and calibrating the agent-based model 42
3.3.1 Verification 42
3.3.2 Sensitivity analysis 42
3.3.3 Calibration 42
3.4 Analysing results and finalizing research 43
3.4.1 Analysis of the results 43

3.4.2 Finalizing research 43
4. Data collection and analysis 44
4.1 GAET travelling 44
4.2 Visit travelling 44
4.2.1 Processing answers 45
4.2.2 Survey results 45
4.3 Tests and hospitalization 49
4.3.1 Tests 49
4.3.2 Hospitalization 50
5. Verification, sensitivity analysis and calibration 51
5.1 Verification 51
5.1.1 Travelling 52
5.1.2 Lockdowns 59
5.1.3 Change of contact matrix 63
5.2 Stability model 65
5.3 Sensitivity analysis 66
5.3.1 Transmission rate 66
5.4 Calibration 68
5.4.1 Patterns graphs 69
5.4.2 Calibration seasonal transmission rate 70
5.4.3 Calibration age groups 74
5.4.4 Infectious period 76
5.4.5 Day of the outbreak 77
5.4.6 Conclusion 79
6. Analysis and results 80
6.1 The three scenarios 80
6.1.1 Roadmap scenario 80
6.1.2 Economic scenario 81
6.1.3 Age scenario 83
6.2 Results scenarios 84
6.2.1 Roadmap scenario 84
6.2.2 Economic scenario 86
6.2.3 Age scenario 88
6.2.4 Comparison of scenarios 89
7. Discussion and limitations 95
7.1 Limitations 96
7.1.1 Calibration 96
7.1.2 Model 96
7.1.3 Outcomes 97
7.1.4 Data 97
8. Conclusion and recommendations 99
8.1 Further Recommendations 101
8.1.1 Calibration 102
8.1.2 Model 102
8.1.3 Outcomes 102
8.1.4 Additional recommendations 103
8.1.5 Data 104
8.2 Conclusive remarks 105
9. References 106
10. Data sources 113

11. Appendices 114
Appendix A 114
Appendix B-1 116
Appendix B-2 117
Appendix C 119
Appendix D 123
Appendix E-1 124
Appendix E-2 125
Appendix E-3 126

1. INTRODUCTION

The novel coronavirus 2019 (SARS-CoV-2) is a highly infectious virus that caused an epidemic that turned into a pandemic over the course of few months. The spread of the virus started in December 2019 in Wuhan, China, and the virus has rapidly spread across the globe (Xu et al., 2020). The timeline in Figure 1 summarizes the main COVID-19 events worldwide, with a focus on Europe. In the year 2020, it was estimated that the virus had already infected 83.9 million people worldwide (World Health Organization, 2020b). The expectation is that this number, in reality, is even higher as not all cases are tested and documented. The highest numbers of documented infections per country in 2020 are in the United States (US) and India. On 31 December 2020, the US had almost 19.7 million known cases and in India 10.3 million cases were reported (World Health Organization, 2020b). The virus, SARS-CoV-2, is the cause of Corona Virus Disease (COVID-19), which can cause symptoms like coughing, shortness of breath and fevers (Lai et al., 2020; Xu et al., 2020). In the worst-case scenario, the virus results in the death of the infected individual.

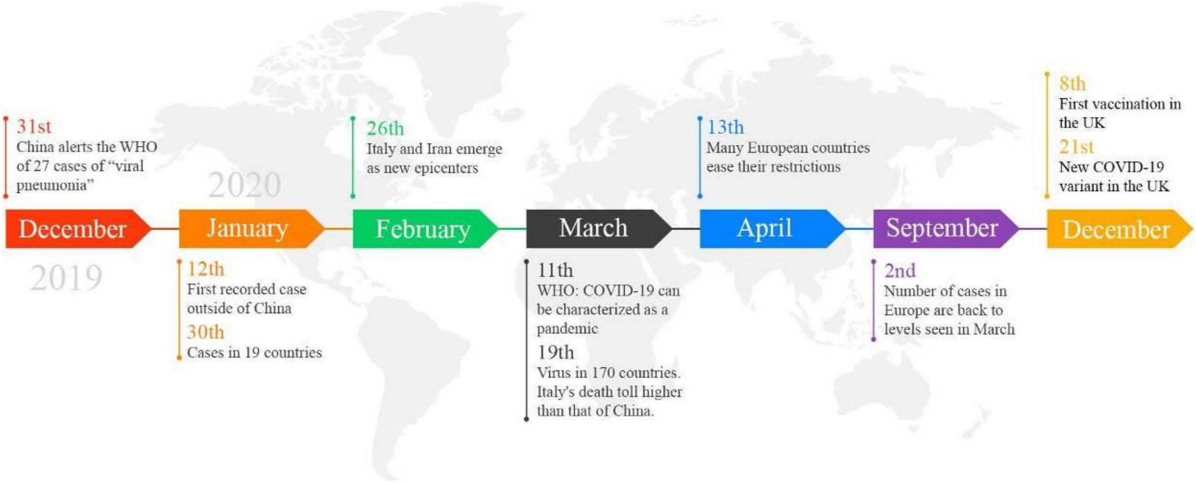

Figure 1. Timeline COVID-19 worldwide with a focus on Europe 2019 and 2020. Based on data from World Health Organization (2020a) and Wu et al. (2020).

In the Netherlands, the first person tested positive for corona on 27 February 2020 (Ministerie van Algemene Zaken, 2020a). During the time leading up to the first positive test result, it is assumed that already several people were infected without knowing it. A summarization of the main COVID-19 events in 2020 in the Netherlands is shown in Figure 2. The virus started in the province of Brabant and the celebration of Carnival had a great contribution to the spreading of the disease. On 23 March 2020 measures were taken by the Rutte III cabinet which resulted in an 'intelligent lockdown' (Ministerie van Volksgezondheid, Welzijn en Sport, 2020a), a lighter version of a full lock-down. During the time COVID-19 has been active, several press conferences have been used to inform the public of new corona measures (Ministerie van Algemene Zaken, 2020b). On 10 April 2020, the level of infections reached the highest point of the first wave. The number of infections eventually reduced, only to show new peaks in September (Figure 3). The numbers, shown by the RIVM, do not include all the infected individuals in the Netherlands, because not all people who contract COVID-19 are tested. The actual numbers in the Netherlands are expected to have been higher.

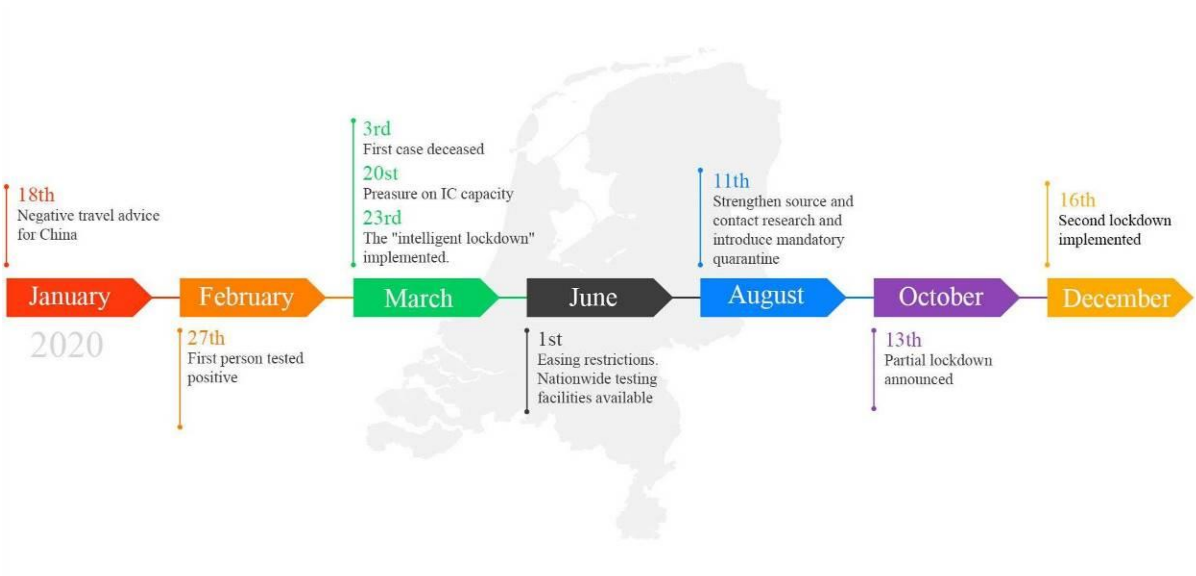

Figure 2. Timeline COVID-19 the Netherlands 2020. Based on data from Ministerie van Algemene Zaken (2020d).

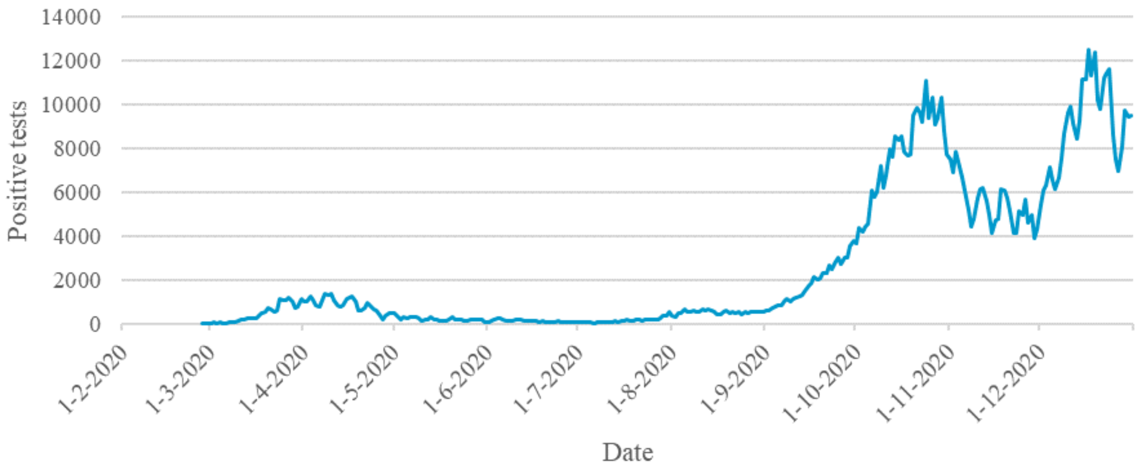

Figure 3. Positive COVID-19 tests in the Netherlands 2020 (data source: RIVM[6], 2021).

On 6 January 2021, The Netherlands began vaccinating their population. At the moment, around 5.5 million vaccine doses have been administered (01-05-2021) (Ministerie van Volksgezondheid, Welzijn en Sport, 2021). As there was no treatment in 2020 yet, the virus had to be controlled by measures taken by governments globally, such as social distancing, quarantine, isolation, or community containment. According to the study of Flaxman et al. (2020), measures like these do reduce the transmission rate. The measures also decrease the mortality rate and ensure that hospitals are not overburdened. However, such measures only work when all citizens contribute. Models can be very useful to evaluate the effectiveness of these measures and predict the expected results of different combinations of interventions. For this purpose, models are needed that simulate the spread of the disease, the interventions a government can take and the response of the general public. This response of citizens to both the disease and the control interventions taken by their government is complex.

The Protection Motivation Theory can be used to divide the decision-making process of the citizens and government into two steps: risk assessment and coping appraisal (Rogers, 1975). In the risk assessment phase, people assess the severity of the risks and analyse the severity of the situation. Afterwards, during the coping appraisal, the action that is to be taken by the citizen or government is decided. The Protection Motivation Theory (Rogers, 1975) is very useful to better understand the public's willingness to cooperate and follow the measures set by the government. The ongoing COVID-19 pandemic emphasised the impact of behaviour change in our daily lives on the spread of the virus. If a citizen experiences risk, it can influence the behaviour of the citizen. Eventually, the citizen will take the decisions to have a protective response. Therefore, accurate risk perceptions of a country and its citizens are crucial to managing COVID-19.

Risk perception does not only take place at the level of the individual. Also, the government performs a risk perception and bases intervention measures on the risk they perceive. The choice of intervention is in fact the coping appraisal. Both individual and governmental risk perception and coping appraisal influence each other. The theory of Rogers (1975) does not include risk perception at two different scales (the scale of the individual and the scale of the national government) and how these two levels influence each other, but focusses on the individual risk perception and coping appraisal, although it also can be applied on other scales. The government can perceive risk as well and take strategic measures that influence individuals. This can also work vice versa: citizens perceiving risks can influence the government into taking steps against the virus. These interactions are complicated, as the two levels continuously influence each other. This can be explained by using an example: the face mask discussion. The face mask discussion started right after the first few COVID-19 cases were identified. The Dutch government did not give an urgent advice or make it mandatory to wear face masks till the end of September (NOS, 2020b). During this time, there was an increase in the number of infections (Figure 1). Many citizens wanted to make the face mask mandatory in public spaces but there was also a counter group that did not. At this time, wearing face masks in public spaces was already mandatory in other countries like Italy, Spain and Germany (NOS, 2020a). The discussions contributed, together with health experts advice, and the rising infection level, to the fact that the Dutch government gave urgent advice on 30 September 2020 to wear face masks in public spaces and made it mandatory to wear them from 1 December 2020 onwards (NOS, 2020b). In the meantime, many places, including schools, had already made face masks mandatory on their grounds and some citizens already wore face masks when visiting public spaces. This example indicates that citizens can proactively take action by themselves by using protective measurements, without being forced by the government. Citizens can also influence the government to take measures, for example by having demonstrations. But in the end, only after urgent advice was given by the government the number of face masks wearers went up (NOS, 2020b). Therefore it can be concluded that measures and restrictions taken by a risk-perceiving government have a very large impact on the risk perception and coping appraisal of its citizens.

Agent-based models are valuable tools to predict disease cases and test out interventions scenarios. Most existing models do not include behaviour change due to risk perception and governmental restrictions. Abdulkareem et al. (2017) are one of the few modellers that do include risk perception. This risk perception is on the level of the individual, while this thesis focuses on the nationwide level. In this thesis, the risk perception and coping appraisal during the COVID-19 pandemic are studied by agent-based modelling. For the research, an existing model is used. This model was initially created to research the influence of the vaccination rate on pertussis.

1.1 RESEARCH QUESTIONS

The main goal of this research was to evaluate the impact of the governmental risk perception and coping appraisal on the predicted number of disease cases for COVID-19 in the Netherlands with a COVID-19 Netlogo model. An agent-based COVID-19 model will be used to test newly available data. This thesis aims to give insight into COVID-19 through the year 2020 by looking at the effect of government decisions in different scenarios on the number of infected individuals, the reproduction number, the hospitalizations and the virus diffusion. The main question of this research is:

How can the risk perception and coping appraisal in a COVID-19 model help to evaluate different intervention scenarios?

The research question can be split into three sub-questions:

A. *How can the existing pertussis/COVID-19-model be remodelled?*
   - How is the model built?
   - How can the model be updated, so it fits the present COVID-19 pandemic?
   - How can the behaviour of the governmental agent be modelled?

B. *How can the governmental risk perception and coping appraisal be incorporated into an agent-based COVID-19 model?*
   - How can risk perception and coping appraisal be modelled at a governmental level?
   - Which intervention scenarios can be identified and implemented in the model?
   - At what risk level (risk perception) should new measures be implemented (coping appraisal)?
   - How can the updated model be used to evaluate the impact of risk perception and coping appraisal on reproduction number, the number of hospitalizations and the spread of COVID-19?

C. *What are the effects of risk perception and coping appraisal on the number of COVID-19 cases, and the spatial diffusion of COVID-19 in the Netherlands?*
   - What COVID-19 data is available for the Netherlands, and how can this be used to calibrate the COVID-19 model?
   - What are the advantages and disadvantages of each scenario?
   - What are the effects of the risk perception and coping appraisal on the number of infected individuals, the hospitalizations, the reproduction number and the spread of COVID-19?
   - Which spatial patterns are created by risk perception and coping appraisal?

1.2 THE SCOPE OF THE RESEARCH

The goal of the research is to create a better understanding of what the effects of risk perception and coping appraisal are on the number of COVID-19 cases and the spatial diffusion of the virus. The focus lies on the general trends in the number of COVID-19 cases and their spatial distribution. The model will focus on the national level in the Netherlands.
Vaccinations are not taken into account in the COVID-19 model. Vaccinating citizens is a form of coping appraisal and it is already present in the model because it was added by

Tjalma (2016). For future research, it can be interesting to expand this function in the model.
The research is based on recently found data. A lot is still unknown about the virus and a lot of data is not well documented. Therefore, the model will only run for 2020. Once new data will become available in the future, this new data could be used to update the research. As a result, the model is expected to show reliable results for the year 2020, while results can be expected to become less realistic over longer periods. The implementation of such future data into the model lies outside of the scope of this research.
Still, the model can help to create a better understanding of the risk perception and coping appraisal in connection with the virus and measures taken. The model could also be adapted for other countries.

2. THEORETICAL BACKGROUND

This literature review gives an insight into the risk perception and coping appraisal of individuals and the government. The first part of the theoretical background (2.1) discusses how the pandemic started. The second section (2.2) provides the factors necessary to understand the virus such as fatality rates, reproduction numbers, incubation time, symptoms, prevention measures, spatial spread and differences between population groups. The third section (2.3) describes the Dutch approach to COVID-19.

After studying the factors that help gain insight into the COVID-19 crisis in the Netherlands, the Protection Motivation Theory is examined in section 2.4. The model can make people and organizations aware of why they behave a certain way (Rogers, 1975).

Besides studying the Protection Motivation Theory, a different modelling technique is studied: Agent-based modelling (2.5). Most of these modelling techniques are presented in the thesis of Tjalma (2016) and are therefore not explained in this thesis. It is advised to read the thesis of Sietske Tjalma for the theory on agent-based modelling, complex systems, mathematical modelling, network modelling and contact matrices. Furthermore, two Agent-based models are described, which implement risk perception, coping appraisal and disease diffusion in the Netlogo models. The glossary on page 4 provides the reader with explanations of specific words.

2.1 COVID-19: WORLDWIDE

The novel coronavirus 2019 (SARS-CoV-2) is a highly infectious virus. The virus of probable bat origin (Zhou et al., 2020) started to spread in December 2019 in Wuhan, China, on the Huanan seafood market (Huang et al., 2020). On 31 December 2019, the local health authority released an epidemiological alert, and on 1 January 2020, the market was shut down. On the same date, around 59 people that were suspected to be infected, of which 41 later tested positive, were in the hospital with symptoms like dry cough and fever (Huang et al., 2020). A team of specialist, including physicians, epidemiologists, virologist and governmental officials was created to research the new virus. Based on the experiences with the viruses SARS and MERS, several safety measures were advised by the WHO for health workers (World Health Organization, 2020a).

The first recorded case outside of China was discovered in Thailand on 13 January 2020, the days after new cases were identified in Korea, Japan and the USA (World Health Organization, 2020a). The epidemic turned into a global pandemic and the virus rapidly spread across the globe (Xu et al., 2020). On 31 December 2020, it was estimated that the virus had already infected over 80 million people worldwide (World Health Organization, 2020b). The expectation is that in reality, this number is even higher as not all cases are tested and documented. The highest amounts of infected people are in the US and India. On 31 December 2020, the US had almost 19.7 million cases and India had 10.3 million cases (World Health Organization, 2020b). A summary of the main COVID-19 events worldwide in 2019 and 2020 is shown in Figure 1.

2.2 COVID-19: RESEARCH

In this section, current COVID-19 research is discussed. It must be taken into account that COVID-19 is a relatively new virus, thus many aspects of the virus are still unknown. In section 2.2.1 the potential symptoms of an infected individual are explained. Afterwards, in section 2.2.2 the variables with which the COVID-19 can be measured, such as the reproduction number, the serial interval, the incubation period, the infectious period and the duration of immunity, are discussed. Afterwards measuring spatial spread (2.2.3), COVID-19 prevention (2.2.4), COVID-19 and different age groups (2.2.5), similar viruses (2.2.6) and seasonality (2.2.7) are explained.

2.2.1 Symptoms

The virus is the cause of Corona Virus Disease (COVID-19), which can cause damage to the cells of the airways and lungs, causing irritation and infection. This is often accompanied by symptoms like dry coughing, a sore throat, a runny nose and/or shortness of breath (Hu et al., 2020; Huang et al., 2020; Lai et al., 2020; Xu et al., 2020). The body reacts to this infection by producing cytokine molecules (Tang et al., 2020). These help to mediate immunity, but can often cause fever, fatigue, muscles aches, a loss of appetite and headaches. If the virus is present in the stomach or belly an infected individual can have diarrhoea, nausea and can have a need to vomit. In the worst-case scenario, the virus results in the death of the infected person (Hu et al., 2020; Huang et al., 2020; Lai et al., 2020; Xu et al., 2020). However, most people infected with COVID-19 only have mild symptoms. It is even possible that a person does not have any symptoms at all (Hu et al., 2020). For severely infected individuals, lung infections (pneumonia) are most common (Huang et al., 2020). If larger areas of the lungs get infected, the lungs cannot perform normally and less oxygen can enter the blood. This causes the body to breathe faster, leading to many severe cases that suffer from shortness of breath. This can be very dangerous for the patient and hospitalization is often necessary. COVID-19 can also cause organ failure, which results in death if not treated (Wang et al., 2020).

2.2.2 Measuring Transmission

A person can be infected with the coronavirus via nose and eyes or by the virus being inhaled (direct transmission), or via a contaminated surface that directly touches the mouth (indirect transmission). When a person talks, coughs, sneezes or sings the SARS-CoV-2 can be transmitted via saliva, respiratory secretions or respiratory droplets (Huang et al., 2020; J. Liu et al., 2020). The reproduction number, serial interval, incubation period, infectious period and immunity after infection are all variables with which the transmissions from person to person can be measured. Each of these variables is discussed below.

Reproduction number

Infected individuals can spread the virus to other people in their surroundings. The reproduction number (R_0) is the average number of people a COVID-19 case infects (van den Driessche & Watmough, 2008). This number gives more insight into the spread and control of COVID-19 and can be used for other viruses. The reproduction number is often used in models and simulations predicting the future number of cases. If this number is higher than 1, more people will become infected and the epidemic grows. If it's lower than one, the cases drop. If $R_0 = 1$, the number of cases stay the same (van den Driessche & Watmough, 2008). According to data from the RIVM (Rijksinstituut voor Volksgezondheid en Milieu, 2020g) and according to Liu et al. (2020) at the beginning of the spread of the virus in January when there were no control measures, the reproduction number lay between 2 and 3 (i.e. $R_0 = 2$ or

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R_0 =3). As soon as R_0 is larger than 1 the amount of infected individuals starts to grow exponentially. Depending on the way people interact in different locations and population groups, the R_0 may differ. If the $R_0 = 2$, the transmission rate should reduce at least 50% to get the R_0 below 1. In the case of a R_0 of 3, this is 66%. According to Sun et al. (2020), the transmission rate of COVID-19 without government interference must be around 2.2.

Serial interval

The serial interval is the time between the primary case showing symptoms (the infector) and the secondary case (the infected) showing symptoms. The serial interval of COVID-19 is estimated to be around 3.96 days according to Du et al. (2020), who studied 468 COVID-19 transmissions. According to a more recent study the serial interval is around 5.40 and 5.19 days (Rai et al., 2020). The serial intervals are important to calculate the R_0. If the serial interval is around 4 days then with $R_0 = 2$ the number of cases will double every four days.

Incubation period

The incubation period is the number of days between when you are infected and when you have symptoms. The incubation period of COVID-19 can help us to understand the quarantine period needed for potentially infected cases to reduce the chance to infect others. Lauer et al. (2020) estimated the median incubation period to be 5.1 days in March. For 97,5 % of the cases symptoms developed within 11.5 days. On 18 August 2020, the quarantine time in the Netherlands was reduced from 14 to 10 days. The Outbreak Management Team (OMT) advised this based on Dutch source and contact research. According to them, 99% of the cases experienced symptoms within 10 days after the infection took place (Rijksinstituut voor Volksgezondheid en Milieu, 2020a).

Infectious period

Exact data on the infectivity period is still lacking. The infectious period is the period in which an infected individual is capable of transmitting the virus directly or indirectly to another individual. There are many variations in the estimations of the infectious period according to Byrne et al. (2020). Hu et al. (2020) define the infectious period as the time from diagnosis to the time of the first two clear tests. The LCI, the Dutch provider of step-by-step plans and scenarios that are created by professionals in infectious disease control, states that the infectious period starts one day before the symptoms and ends five days after the first symptoms in most cases (Rijksinstituut voor Volksgezondheid en Milieu, 2021). This is in accordance with He et al., (2020) and Zou et al. (2020) who researched the most infectious period of patients, although they indicated in their papers that a person could also be infectious two days before the symptoms start. According to Hu et al. (2020), symptomatic patients could have an infectious period of 9.5 days, while asymptomatic patients could have a shorter infectious period of 4.0 to 6.0 days. It is still hard for researchers to identify whether a patient has no, mild or early symptoms, which makes research concerning the infectious period rather difficult.

Duration of immunity

The duration of COVID-19 immunity is the time during which the human body can protect itself against the virus. Many researchers are still working on this topic because the virus is relatively new. One research assessed that the immunological memory of SARS-CoV-2 is up to eight months after infection (Dan et al., 2021). Although it seems that individuals have more than eight months of immunity after being infected, it can still happen that an individual gets infected more than once within the eight months (Dan et al., 2021).

2.2.3 Measuring Spatial Spread

Disease diffusion tends to be different over time. This also applies to the intensity of a disease, which can be indicated by the mortality or fatality rate. These changes differ over time due to the changes in the physical and social environment. The type of disease influences the geographical distribution and the level of infectiousness and severity of the disease also influence the spread. Environmental change (i.e. seasonality) and the increase in mobility of individuals impact the spread. This causes the creation of new approaches on local, national and global levels to fight the resulting public health issues (Schærström, 2009). The geographical study of diseases focuses on the location, the number of cases and the direction and pathways that a disease has. The geographical circumstances that lead to the spread of the disease are also studied. There are two distinctions in the spatial diffusion theory: the dispersal and the structural dimension (Schærström, 2009). The dispersal aspect of diffusion involves the movements and directions of a disease. This dimension is either contagious or hierarchical. Hierarchical diffusion refers to the transmission through an ordered sequence of places or classes. Contagious diffusion is the spread of a disease through direct contact with an infected. In this case, the diffusion is influenced by distance: individuals in nearby areas have a higher chance to get infected than individuals in remote areas. The structural aspect concerns the relationships that different locations have with each other. The structural dimension is characterized by either expansion or relocation. Expansion diffusion refers to the spread of a disease from one source outwards to new areas. Relocation diffusion is similar to expansion diffusion, but during this diffusion the source of the disease is left behind (Schærström, 2009). The different diffusion processes are shown in Figure 4.

The spread of COVID-19 is a combination of expansion and relocation diffusion (Kuebart & Stabler, 2020). The virus expands to different regions and often dies out in the origin location, due to new measures. There are certain areas in the Netherlands, where it seems that the virus never really dies out. In these areas, such as Rotterdam or Amsterdam, the number of infected people can be really low and then increase again but never die out. People who were infected are possibly not immune and a second infection is possible. This results in a greater chance for the virus to spread again in areas with a high infection rate. Kuebart & Stabler (2020) researched the socio-spatial processes during the COVID-19 outbreak. They conclude in their paper that super spreading events accelerate the outbreak. Super spreaders are individuals, who infect a relatively high number of individuals in a specific place. Often this takes place in crowded places with poor ventilation (Kuebart & Stabler, 2020). These super spreading events can cause regional outbreaks. Tourist mobility causes widespread relocation diffusion because tourists import the infection when returning from their holiday. School and job mobility can also cause relocation diffusion but on a lower scale.

2.2.4 COVID-19 prevention

Since 7 January 2021, the Dutch government started to vaccinate citizens and it is estimated that the process to vaccinate the citizens will take almost a year. In 2020 there was no vaccination available yet. Therefore, to reduce the reproduction number, the contact between infected and healthy people had to be reduced. One way to reduce this contact is to isolate individuals who are showing COVID-19 symptoms. Another way is to apply social distancing, during which the whole population has limited contact with each other. According to the study of Flaxman et al. (2020), these measures reduce the transmission rate significantly. Lockdowns are an effective way to reduce the spread of COVID-19, but the downside is that it is disruptive both economically and socially.

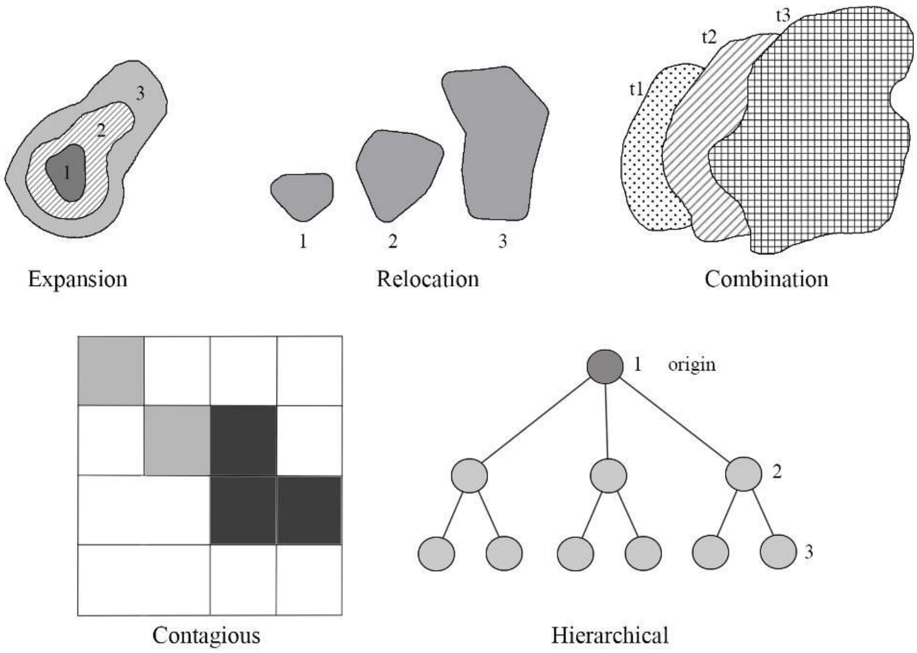

Figure 4. Processes of spatial diffusion (based on Cliff et al., 1981; Tjalma, 2016).

To lower the economic and social impact of the virus tests are executed. If an individual tests positive, you can take protective steps to take to prevent others from getting sick. If an individual tests negative, the person does not have to isolate and can return to normal (working) life sooner, which is both economically and socially more beneficial. A COVID-19 test during an active infection detects the genetic fingerprint of the virus. Another test identifies if there are antibodies against the virus in the body (Rijksinstituut voor Volksgezondheid en Milieu, 2020e). With the anti-bodies detection test, you can check if someone was infected in the past. The first test can be performed to detect COVID-19 in the throat or nose even before a person has symptoms. It is even possible that a person without symptoms still tests positive and infects other people. A few days later, the symptoms can recede and the amount of antibodies increases. From that moment on the second test can be performed (Rijksinstituut voor Volksgezondheid en Milieu, 2020e).

2.2.5 COVID-19 and different population groups

Risk groups for COVID-19 are people over the age of 70, adults with underlying health conditions, such as heart problems, high blood pressure, chronic respiratory or pulmonary problems, diabetes, cancer and kidney disease (Clark et al., 2020).

Children usually have only mild symptoms (Jiehao et al., 2020). Hoek et al. (2020) in their study based on Dutch COVID-19 notification data suggest that most transmissions take place between adults of the same age groups. Children are mostly infected by adult family members. Children infecting adults and children infecting other children seems to happen less often. There are still ongoing investigations in this area. Especially children from 1 till 11 were seen to be tested positive less frequently, compared to older children and adults. A study in Ireland (Heavey et al., 2020) shows evidence that children are no drivers of transmission and a study in Iceland (Gudbjartsson et al., 2020) confirms that children younger than 10 rarely test positive. In Figure 5, the spread of COVID-19 in different age groups is shown. The data up to 14 September 2020 is used, with information of 7641 patients. Most transmissions are between people of the same age. The figure shows that transmission mostly takes places in the same age groups and less between parents and children. Young children of 0-9 year old barely infect others in their age group.

The same study in Iceland (Gudbjartsson et al., 2020) discovered that fewer females were tested positive than male (11.0% vs. 16.7%). The RIVM (2020b) shows that relatively more males die decease because of COVID-19 than females. An international study by Sharma, Volgman, and Michos (2020) concludes that not enough attention is given to the differences between men and women concerning COVID-19. There are indications that their biological differences cause them to react differently to the virus. Furthermore, there are behavioural and social differences between the sexes that possibly favour women. Pre-COVID-19 studies suggest that woman are more likely to wash their hands or seek preventive care (Bertakis et al., 2000; Johnson et al., 2016).

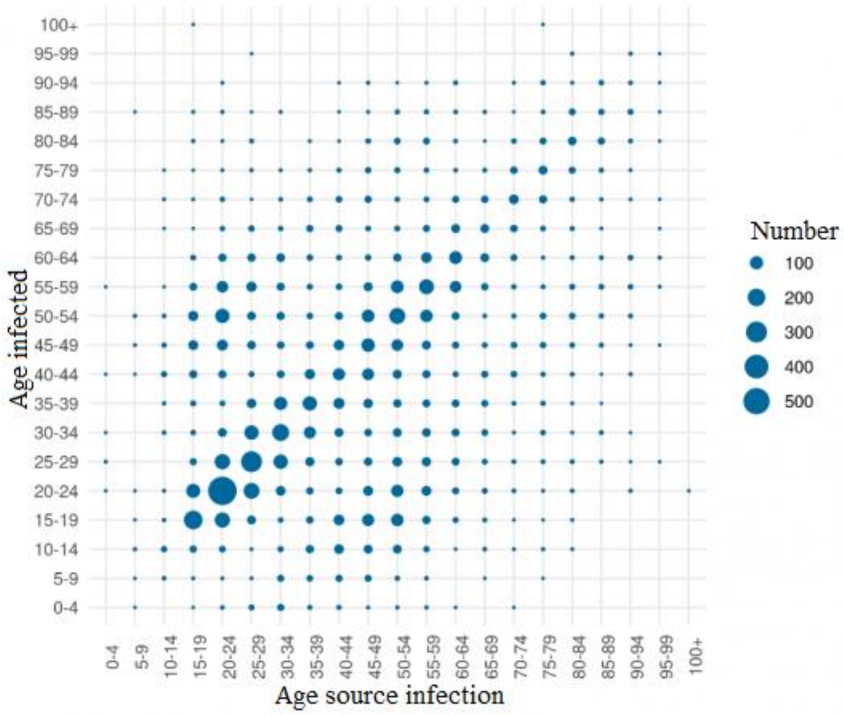

Figure 5. Spread of COVID-19 in age groups in the Netherlands (Rijksinstituut voor Volksgezondheid en Milieu, 2020d).

2.2.6 Similar viruses

To understand similar viruses two common ratios need to be explained: The infection fatality ratio and the case fatality ratio. The two ratios are used to determine the number of deceased in comparison to the number of infected and can be used to compare different viruses. The infection fatality ratio (IFR) represents the number of deceased among all infected. This includes undiagnosed infected individuals (Hauser et al., 2020). The case fatality ratio (CFR) represents the deceased among identified and confirmed cases (Hauser et al., 2020). The IFR also tries to take into account the hidden infections. Hidden infected individuals are people who appear to be healthy but still carry the virus. These hidden infected individuals could still infect others and therefore spread the virus. By taking into account the hidden infected individuals the IFR tries to use a realistic prediction to base the ratio on. This makes the IFR more usable than the CFR when comparing different countries. Still, the IFR of one country does not always match other countries. The IFR can differ per country and it depends on the number of tests, estimated infected, quality of health service, transmission rate (Hauser et al., 2020). The IFR is often higher or lower than in reality.

Influenza is present all the time in the population and causes many deaths each year. According to data from the UK, around 0.1% of influenza cases die of the common seasonal flu. The exact death rate of COVID-19 remains quite unclear. During the initial period of the spread of COVID-19, the rate in China was around 15%. This is mostly due to little knowledge available regarding the virus and possible treatments. Articles (Hauser et al., 2020; Russell et al., 2020; Verity et al., 2020) from March indicate that the CFR is around 1.2-2.4% and the IFR around 0.5-1.4%. Research of the RIVM (2020a) estimates the IFR to be around 1%. Hauser et al. (2020) and Verity et al. (2020) both indicate that the IFR is much higher for people who are older than 60. Compared to the common flu with an IFR of around 0,1%, COVID-19 is clearly more dangerous.

A coronavirus was discovered in a human population in the twenty-first century twice before COVID-19: the severe acute respiratory syndrome (SARS-CoV, or SARS) in 2002 and the Middle East respiratory syndrome coronavirus (MERS-CoV, or MERS) in 2012. SARS-CoV started in China and spread to other countries, such as Vietnam and Canada. From the 8,096 reported cases in 27 countries, 774 were deceased by July 2003 (World Health Organization, 2003). From this moment on no other cases were discovered from this SARS pandemic. It was suspected that the virus was transmitted from a bat to a civet cat and from a civet cat to a human (Wit et al., 2016). The CFR for SARS was around 10% (Müller et al., 2015).
MERS was discovered in June 2012. This virus eventually resulted in 1,728 cases and 624 deaths in 27 countries (World Health Organization, 2016). The diffusion of the virus went on till the 26th of April 2016. The virus was first transmitted by dromedary camels, who likely contracted it from bats (Wit et al., 2016). The CFR was around 36% (World Health Organization, 2016).
Compared to the flu and other Coronaviruses, COVID-19 is more highly transmissible, but the CFR is lower than SARS-CoV and MERS. However, the CFR of COVID-19 is higher than the CFR of the common seasonal flu.

2.2.7 Seasonality

The study by Merow & Urban (2020) found that especially UV light is associated with the decrease of the virus transmissions. This agrees with the research of Ebadi & Montano-Loza (2020), who found that a high dose of vitamin D, especially obtained from sunlight, can potentially decrease the risk of infection. Merow & Urban (2020) predict that the number of infections decrease during summer, rebound by autumn and peak in the winter within a temperate climate. The patterns in the Netherlands, which also has a temperate climate, do not contradict these findings (Rijksinstituut voor Volksgezondheid en Milieu, 2020b). Another study, by Ozyigit (2020), found that a 1 °C increase in temperature results in a reduction of the transmission rate of 0.9 percent. Multiple studies provide evidence for the effect of seasonality on COVID-19, however, there is still a lot of uncertainty in the seasonality of COVID-19 research, because the virus has only been around for a year.

2.3 COVID-19: The Netherlands

In the Netherlands, the first person tested positive for corona on 27 February 2020 (Ministerie van Algemene Zaken, 2020a). However, likely, the virus had widely spread throughout the Netherlands beforehand. The virus started in the province of Brabant, and the celebration for

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Carnival had a great contribution to the spreading of the disease. On 23 March 2020 measures were taken by the Rutte III cabinet for the public health, which resulted in an 'intelligent lockdown' (Ministerie van Volksgezondheid, Welzijn en Sport, 2020a). Measures taken by the national government were used to prevent people from meeting in groups and spreading the virus. During this lockdown, citizens should stay at home as much as possible. If someone was sick in the household, the whole household was obliged to stay home. During the time COVID-19 is active, press conferences are used to inform the public of the new corona measures (Ministerie van Algemene Zaken, 2020b). The social and economic consequences hit the whole of the Netherlands. To lower the impact of the virus on the economy and the citizens, the government chose to support people and companies with difficulties with a special fund. On 10 April 2020, the number of infected people reached the highest point of the first wave (Rijksinstituut voor Volksgezondheid en Milieu, 2020b). The infected people mainly lived around the south of the Netherlands. The number of infected people eventually reduced, only to show new peaks in September and October. During this peak, the virus was present throughout the whole country and did not remain confined mostly to the south of the Netherlands, like the first wave. Many municipalities which were quite unharmed during the first peak had a rise in the number of infected citizens (data source: RIVM[2], 2021). A summary of the main COVID-19 events in the Netherlands in 2020 is shown in Figure 2.

At the beginning of the epidemic, the Dutch government did not want to implement local measures for the municipalities which were most affected. Around August, several large municipalities saw a rise in infected cases and decided to implement local measures themselves. During this time, the government also changed its view and applied new additional measures to local areas, safety regions and municipalities with outbreaks (Ministerie van Algemene Zaken, 2020e). The Netherlands consists of 25 safety regions. These regions have agreements on how to deal with disasters and crises. They work together with governments, emergency services, companies and citizens.

The RIVM has a Center for Infectious Disease Control (CIb), which has a coordinating role in combatting the virus. The Director is Jaap van Dissel, a familiar face during the epidemic for inhabitants of the Netherlands (Rijksinstituut voor Volksgezondheid en Milieu, 2020c). Together with the GGDs (Municipal Health Services), representatives and experts, they advise how outbreaks can be controlled. The RIVM (2020) "advises on control measures, contributes to the development of new laboratory diagnostics and charts epidemiological developments utilizing surveillance and research". The RIVM also provides scenarios and guidelines on COVID-19. The RIVM can ask the Outbreak Management Team for advice regarding the outbreaks of infectious diseases or other international threats. The team consist of experts, professionals and people with an important role concerning the disease. The RIVM (Ministerie van Algemene Zaken, 2020c) composed basic rules on what citizens should do to avoid getting infected and avoid infecting others:

- Work at home unless it is not possible;
- Avoid crowds;
- Keep 1.5-meter distance;
- Sneeze or cough in your elbow;
- Wash or disinfect your hands frequently;
- Stay at home if you feel unwell and get tested;
- Wear a mask in public spaces.

On 15 March 2020, about 100 cases were hospitalized in Dutch ICs (intensive cares) (Landelijk Netwerk Acute Zorg, 2020). Most of these cases were located in Noord-Brabant and Limburg, where the virus was mostly located. This impacted the local hospitals and caused a delay in normal health care. To release pressure on the hospitals, patients were transferred to hospitals in other parts of the country. Eventually, a structure was arranged to divide and spread COVID-19 patients, which was named National Network Acute Care (LNAZ) (Landelijk Netwerk Acute Zorg, 2020). At this time, Germany helped to care for a few patients, because Germany did not have many patients yet and has relatively more IC beds. On 20 March, the National Network Acute Care (LNAZ) was asked by the Ministry of Health, Welfare and Sport to create the National Coordination Center for Patient Distribution (Landelijke coördinatiecentrum patiënten spreiding: LCPS) (Landelijk Netwerk Acute Zorg, 2020). From that moment, IC-beds through the country have been available for all the COVID-19 patients that need to be hospitalized.

Before COVID-19, an average of 925 patients was on the IC, while the maximum capacity in the Netherlands was a total of 1.150 IC-beds (Landelijk Netwerk Acute Zorg, 2020). On 7 April 2020, 1.424 COVID-19 patients made use of the ICs. This high number caused extreme pressure on healthcare. In the IC-bed upscaling plan it is planned to add 650 extra IC beds. This is quite a task because each IC-bed needs 3,0 FTE (full-time equivalent, e.g. hours worked by one employee on a full-time basis) IC-nurses and 0,6-0,9 FTE IC-doctors (Landelijk Netwerk Acute Zorg, 2020). Therefore, a higher number of IC-beds requires a higher number of health professionals. The Dutch IC-bed upscaling plan takes 3 steps: 1050 beds (100%), 1350 beds (120%), 1700 beds (150%) (Landelijk Netwerk Acute Zorg, 2020).

The GGDs are responsible for testing and report the results to the RIVM. Citizens with COVID-19 symptoms can get tested for free at one of the test locations provided by the local GGD. A GGD consist of several municipalities. Citizens with crucial jobs, such as nurses and teachers, have priority over other citizens.

2.4 PROTECTION MOTIVATION THEORY

The Protection motivation theory (PMT) can provide a useful framework to understand the protective choices of people. It can help to gain more knowledge on fear appeals by identifying the variables involved and their effects. The PMT was first introduced by Rogers in 1975 and is often used to understand and predict health behaviour. In 1983 the PMT was updated by Rogers to make it broader. The updated PMT identifies four factors (Rogers, 1975; Rogers & Maddux, 1983):

- The perceived severity of a threat;
- The perceived probability of the occurrence (vulnerability);
- The efficacy of the recommended preventive behaviour;
- The perceived self-efficacy.

The protection motivation of an individual arises from the threat appraisal (risk appraisal/perception) and the coping appraisal. These are discussed in section 2.4.1 and 2.4.2.

2.4.1 Threat appraisal

During the threat appraisal, the potentiality and the level of a threat are assessed. This is also called risk perception. This process consists of appraising the severity of a threat and the perceived probability of the occurrence (Rogers, 1975; Rogers & Maddux, 1983). Unhealthy behaviour can still have positive aspects; these are called rewards. The amount of threat experienced is the severity and the probability of a threat minus the rewards.

2.4.2 Coping appraisal

During the coping appraisal, an individual decides how to respond. This consists of assessing the response efficacy, self-efficacy and response cost (Rogers and Maddux 1983). Efficacy is the ability to produce an expected or satisfying result. Self-efficacy is the belief of an individual that he or she can act to gain the desired results. The response costs are the costs necessary to reach the desired results, these can be physical and psychological (Milne et al., 2000; Rogers & Maddux, 1983). The response efficacy and the self-efficacy minus the response cost is the experienced coping ability of an individual (Rogers and Maddux 1983). In Figure 6, a schematic representation of the protection motivation theory is presented.

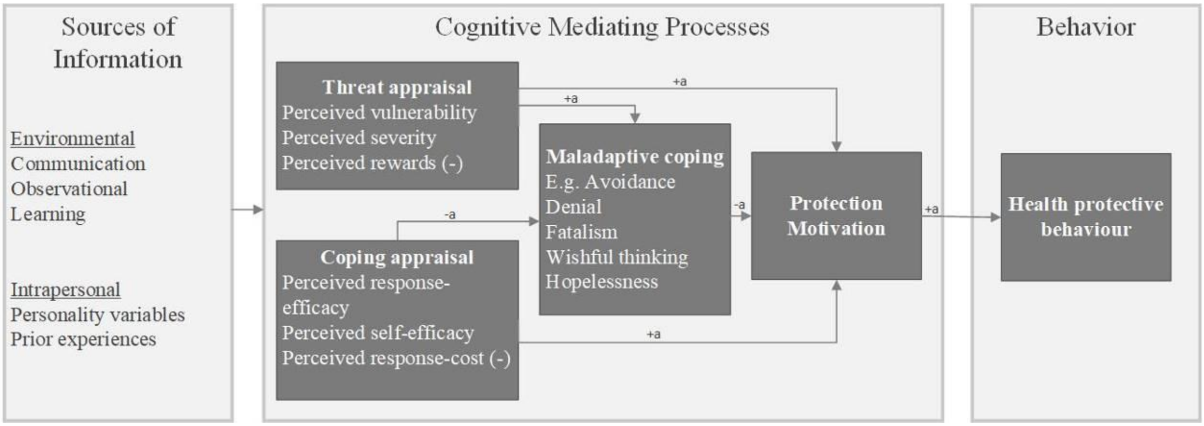

Figure 6. The Protection Motivation Theory. +a = positive association, -a = negative association. (Based on *Milne et al. 2000; Rogers 1975; Rogers and Maddux 1983).*

The Protection motivation theory confirms that a high level of perceived risk results in individuals adopting protective behaviour. The public risk perception depends on how the public perceives the severity and probability (vulnerability) of an infectious disease (Rogers, 1975). To increase the risk awareness of the public during an epidemic, the information should be spread by various sources, such as the government, health care and media (Weerd et al., 2011). Doing this will make the public adopt protective measures, but only if they trust the sources. Weerd et al. (2011) discovered during their Dutch study that during a pandemic the health care workers and municipal health services are the most trusted source of information. The lowest level of trust is given to the media. During a pandemic the government is advised to publish all the available information, to retain and gain trust. The published information should not contradict itself over time, this lowers the trust in the government (Weerd et al., 2011).

2.5 AGENT-BASED MODELLING

This section examines the agents (2.5.1) and their relationships (2.5.2) and environment (2.5.3) in agent-based modelling. Afterwards, two examples of agent-based models are discussed (2.5.4 and 2.5.5).

An agent-based model (ABM) can simulate the individual actions and interaction of various agents, instead of only representing the general behaviour of a population. Such a model takes into account the heterogeneity of geographical systems, spatially as well as temporally (Crooks & Heppenstall, 2011). The models are ideal to simulate human behaviour in systems. An ABM allows a researcher to measure the behaviour and reactions of diverse agents over time. The biggest challenge is to realistically simulate the processes. An ABM consist of three elements used to build a virtual world of a real-world system (Macal & North, 2014):

- Agents and the attributes and behaviours of these agents;
- Agent relationships and the methods of interaction;
- Agents' environment.

The relationships of agents are defined by underlying topology, which determines with whom and how agents interact. The environment an agent lives in can also help to determine how an agent interacts (Macal & North, 2014).

2.5.1 Agents

There is no exact definition of an agent. A few characteristics agents have are (Crooks & Heppenstall, 2011; Macal & North, 2014; Wooldridge & Jennings, 1995):

- Autonomy: agent can make independent decisions, based on processed information.
- Heterogeneity: autonomous individuals are permitted to develop. These can have attributes such as sex, age, education and health status.
- Active: examples of active features are:
    - Pro-active/goal-directed: agents often have goals to achieve.
    - Reactive/perceptive: agents can have awareness, a sense of their surroundings and/or prior knowledge.
    - Bounded rationality: agents have limits in their thinking and choices.
    - Interactive/communicative: agents can query agents or neighbourhood.
    - Mobility: agents can be fixed, but it is also possible that agents can move through the space of a model.
    - Adaption/learning: agents can adapt their form with memory or learning. They can adapt to both individual or population level.

Agents can have other characteristics and do not necessarily have all the characteristics and features mentioned above. A simulation can have more than one type of agents.

2.5.2 Agent relationships

The second element of an ABM is the relationships between agents. Rules can affect the behaviour and relationship of agents with other agents or their surroundings. These rules are created by studying literature, doing analyses and/or numerical work. Rules can apply to one agent or a set of agents. A way to describe the relationship between agents is by calling it reactive (only performing actions when triggered by other agents or the environment) or goal-directed (a goal should be achieved) (Crooks & Heppenstall, 2011).

2.5.3 Agents' environment

The third and final element to an agent-based model is the agents' environment. The states of an ABM depend on the collective state of all agents together with the state of the given/defined environment of the agents. The environment an agent operates in can affect the interaction an agent has with other agents or with the environment itself. Often a complex environment results in diversity in the behaviour of agents, but it is also completely possible that a complex environment has relatively simple agents. Types of environments are (Macal

& North, 2014):

- Soup: Nonspatial model. Agents do not have a location attribute.
- Grid or lattice: Also known as cellular automata. Interaction patterns and local information is represented in a grid or lattice. The cells surrounding an agent is the neighbourhood.
- Euclidian space: Agents can move through a 2D or 3D space. The location of an agent is in grid or latitude-longitude coordinates.
- Geographical information system: This system has a relatively realistic geospatial landscape. The agent can move and interact in this landscape. The location of an agent is a geographical unit (for example street name and house number) or geospatial coordinates.
- Networks: The agent location depends on the nodes in the network. The network can be dynamic or static. In a dynamic network, the links are determined through the process. In a static network, the links are specified beforehand.

In Figure 7, the three elements of the ABM are presented. It shows the different relationships and interactions agents can have and the resulting complexity. Furthermore, it presents the connection between the agents and relationships with the environment. The sphere of visibility and influence is the part of the environment that affects the decisions of the agents.

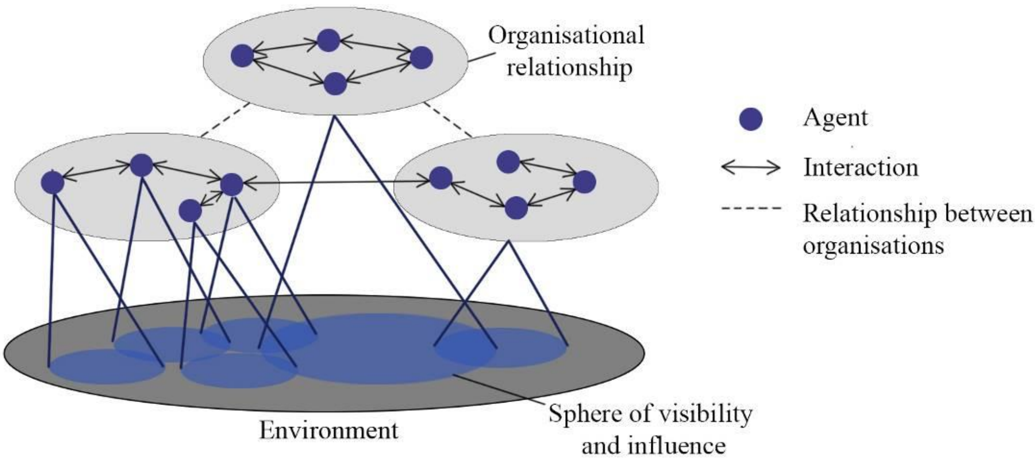

Figure 7. Canonical view of an agent-based system (based on Jennings 2000).

2.5.4 ABM example 1: Bayesian networks for spatial learning

In the research of Abdulkareem et al. (2019) an ABM in Netlogo is combined with machine learning (Bayesian network) in the software R. For the research an already existing ABM, which was created to demonstrate the cholera diffusion in Kumasi, Ghana was used. This model was originally developed by Augustijn et al. (2016). Disease spread and hydrological aspects are steered via the ABM, but risk perception and coping appraisal were implemented via machine learning. The data necessary to train the machine learning algorithm was obtained via a survey. With this data, the model could be calibrated. The survey was used to gather data about the risk perception for cholera. The risk perception of survey respondents was based on visual factors (visual pollution at water collection points) combined with social information (information from neighbours, media etc).

In the ABM, four types of agents are present: individuals, households, media and rain particles. Of these agents, all (except media) have a particular location at each moment. The households that use the Bayesian network also have spatial intelligence. Because of spatial intelligence, the household agents can have an understanding of their spatial environment and can make decisions based on the changes in this environment. Bayesian networks are machine learning algorithms, which are very useful if there is only a small dataset or expert knowledge. In the model, three sub-models are present: a hydrological model, an activity model and a disease model. The activity model includes learning. The following spatial environments are present in the cholera model:

- Elevation surface data;
- Dumpsites;
- House layer with three different income levels: high, medium and low;
- The river;
- The ID and centre of the communities.

The protection motivation theory is used as the theoretical framework. With two Bayesian networks and machine learning algorithms, risk perception and a coping appraisal are represented with the help of the software R. The study mostly focuses on low and medium-income households, because the high-income agents can buy bottled water and avoid getting into contact with cholera. The low and medium-income agents use the first Bayesian network to perceive and evaluate the risk. The risk assessment exists of four criteria: visual pollution, media attention, contact with the neighbour about the subject and previous experiences. The second Bayesian network is used to cope and decide on the kind of water they will use. The agents will then decide if they boil the water, buy water or go to another water collection point.
Abdulkareem et al. (2019) conclude that the balance between survey data and expert knowledge produces realistic agent behaviour and also gives the user great control over the learning process of the different agents. Figure 8 shows the conceptual model of the model created by Abdulkareem et al. (2015).

2.5.5 ABM example 2: Spread of pertussis and vaccination

The ABM created by Tjalma (2016) was used to test eight vaccination strategies for pertussis. The simulation is on the municipal level. Each municipality has a population, which is divided into 9 age groups. From the age group 12 to 17 years, 5 percent commutes to a school in another municipality. The ages of 25 to 65 years also partly commute to their job in another municipality. This results in the spread of pertussis between the municipalities. An extended Susceptible-Exposed-Infectious-Removed (SEIR) model simulates the disease diffusion. A simple version of the SEIR model is shown in Figure 9. The model consist of the infectious rate (β), the incubation rate (σ), the recovery rate (γ) and the rate for recovered individuals that turn back to susceptible individuals (ξ). To determine the disease diffusion in the population, contact and transmission matrices are used in the research. With these matrices and the fraction of the contacts that are infected the rate of disease transmission was calculated. The model also implements ageing, which makes the age groups more dynamic. For the commuting group, holidays are present in the model. During the holidays there is only 20% of normal travelling. In the model also ageing is implemented, which takes place once a month.

In the end, the vaccination strategies could not be completely identified. But this model did prove the possibility to model spatial disease diffusion (Tjalma, 2016). It has great potential and the model is therefore very useful for other disease models.

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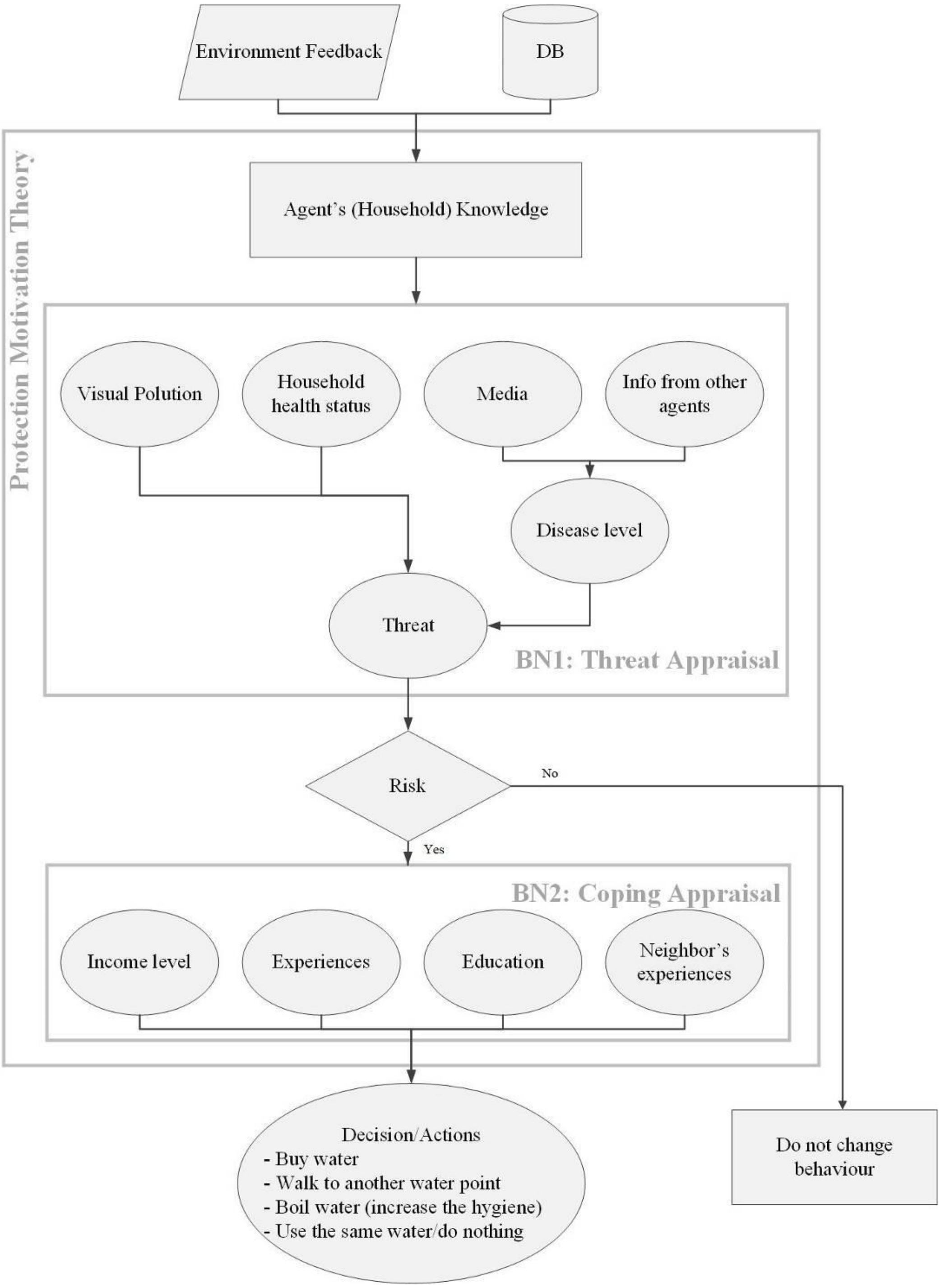

Figure 8. Agent's cognitive model cholera Bayesian network model (Abdulkareem et al., 2015).

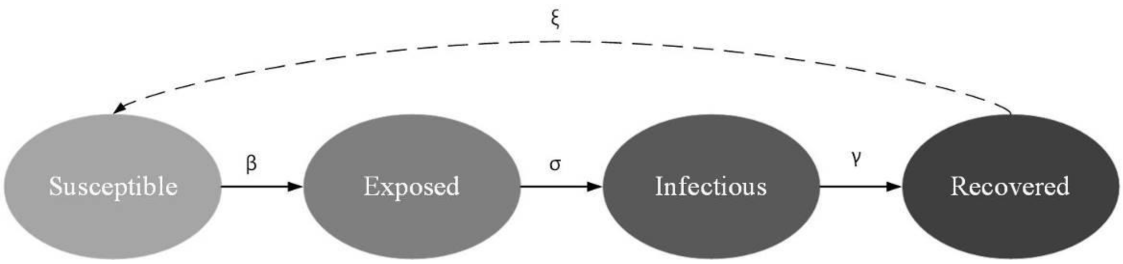

Figure 9. SEIR model.

3. METHODOLOGY

In Table 1, the four different research phases are described. The first research phase, 'Literature and data analysis' includes the theoretical background and the analysis of risk perception and coping appraisal data. By analysing existing risk perception and coping appraisal data the parameters for the agent-based model are determined. After the data is collected it is transformed into a useable shape of data. In phase 2, a conceptual model is developed of how to implement risk perception and coping appraisal at the national level. This conceptual model will be implemented in the existing model in Netlogo. In this phase, the parameters determined and created in phase 1 are implemented. Furthermore, a rule-based approach is used to simulate risk perception and coping appraisal. Eventually, in phase 3, the model needs to be verified and calibrated with the COVID-19 data. Afterwards, different scenarios are run and in phase 4 these scenarios are analysed. The best scenario should be comparable to reality. The model can be used to develop new strategies to influence the citizens' risk perception and coping appraisal.

Phases	Phase includes	Chapter	Result
1. Literature and data collection analysis	Theoretical background & Analysis risk perception and coping appraisal data	2. Theoretical background & 4. Data collection and analysis	Risk perception and coping appraisal factors
2. Conceptual model and implementing variables	Updating existing model	3. Methodology	Agent-based model framework
3. Verifying and calibrating agent-based model	Verification & Calibration	5. Verification, sensitivity analysis and calibration	Working model in Netlogo
4. Analysing results and finalizing research	Analysis of results & Conclusion & Discussion	6. Analysis and results & 7. Discussion and limitations & 8. Conclusion and recommendations	End results

Table 1. Research phases and results.

3.1 LITERATURE AND DATA ANALYSIS

As the virus is still going on during the process of writing this thesis, a lot of COVID-19 related data is collected throughout the whole research period. To make sure the model runs smoothly the COVID-19 data is implemented in the model for each week and not per day.

3.1.1 Theoretical background

A literature study gives an insight into the risk perception and coping appraisal of individuals and the government and how it works. How this can be implemented is studied by analysing existing ABMs. In the first part of the theoretical background, COVID-19 and virus diffusion is researched. After studying several factors that give more insight into the COVID-19 crisis in the Netherlands, the Protection Motivation Theory is examined. The theory creates awareness of the several factors which are used by people or organizations to protect themselves. Besides studying the Protection Motivation Theory, the different modelling techniques are studied. Most of these modelling techniques are presented in the thesis of Tjalma (2016) and are therefore not explained in this thesis. It is advised to read the thesis of Sietske Tjalma for the theory on agent-based modelling, complex systems, mathematical modelling, network modelling and contact matrices. At the end of the theoretical background, two existing agent-based models are discussed. To better understand how to implement risk perception and coping appraisal, a cholera agent-based model is studied. Afterwards, the model of Tjalma (2016) is examined. This gives more insight into how the existing model should be used and adjusted.

3.1.2 Software

Netlogo is an integrated development environment (IDE) for agent-based modelling. It uses its programming language (*NetLogo*, 2020). This program was used to develop the pertussis model and this model will be updated to represent the COVID-19 risk perception and coping appraisal model. Several datasets are already present in the model and will be reused.
Data that is implemented in Netlogo is edited in Excel and transformed into a text file. Netlogo can read these text files by separating them as strings. The geographical data is edited in ArcGIS Pro. For small changes in the data, QGIS is sometimes used.

3.1.3 Geographical data

In the model of Tjalma (2016) data was used from 2013. There were originally 409 municipalities, which were merged into 396 municipalities. By Tjalma (2016) the municipalities with less than 7.5 thousand inhabitants were merged with municipalities with neighbouring municipalities. Table 2 shows the merged municipalities.

Municipalities with <7500 inhabitants	Merged with	Merged municipalities
Baarle Nassau	Gilzen en Rijen	Gilze en Rijen – Baarle Nassau
Graft de Rijp	Schermer	Graft de Rijp - Schermer
Schermer	Graft de Rijp	
Muiden	Weesp	Weesp – Muiden
Rozendaal	Rheden	Rheden – Rozendaal
Vlieland	Texel, Ameland, Terschelling, Schiermonnikoog	Waddeneilanden
Ameland	Texel, Vlieland, Terschelling, Schiermonnikoog	
Terschelling	Texel, Ameland, Vlieland, Schiermonnikoog	
Schiermonnikoog	Texel, Ameland, Terschelling, Vlieland	
Renswoude	Scherpenzeel	Scherpenzeel – Renswoude

Haarlemmermeer	Haarlemmerliede & Spaarnwoude	Haarlemmermeer - Spaarnwoude & Haarlemmerliede
Millingen aan de Rijn	Ubbergen	Ubbergen – Millingen aan de Rijn
Zeevang	Edam & Volendam	Edam & Volendam – Zeevang

Table 2. Merged municipalities 2013 (Tjalma, 2016).

Since then, many municipalities in the Netherlands have been merged, and officially there are 355 municipalities in 2020. Although there are changes in the number of municipalities from the year 2013 to 2020 it is chosen not to update the data. Changing this data does not necessarily change how the model works when the governmental risk perception and coping appraisal is implemented, which is the goal of this study. Therefore, the effect of risk perception and coping appraisal on the number of COVID-19 cases, and on the spatial diffusion of COVID-19 can also be represented with the older data. The GGD regions are also kept the same because these regions are similar to the regions in 2013.
From the vector municipal data, point data is created. This point data represents the municipalities. The points are placed in the middle of the municipalities. The municipal point data is later merged with a table with updated data, consisting of the total population, age groups in the population, commuter data of population and the altered population groups with unique IDs.
The data is changed to the coordinate system WKID 2157 Irish Transverse Mercator (ITM). This is not the ideal coordinate system as it slightly deforms the Netherlands in Netlogo. This coordinate system is chosen because Netlogo could not handle the normal Transverse Mercator, although this should be possible according to the Netlogo website. This also was the case for some other frequently used coordinate systems. The geographical data looks slightly deformed, but this does not take away from the performance of the model and the goal of the research.

3.1.4 Population data

The population data consists of the number of citizens per municipality, age group percentage in municipalities and the percentage of households in the Dutch population. The age groups originally consisted of the age groups: 0 to 5 months, 5 months to 5 years, 5 to 12 years, 12 to 17 years, 17 to 25 years, 23 to 35 years, 35 to 50 years, 50 to 65 years and 65+ years. In this thesis, all age groups include the lower bound, but exclude the upper bound: e.g., 0 to 5 months means $0 \leq \text{age} < 5$ months. The age group 0 to 5 months is not interesting to keep in the COVID-19 model, because it is such a small and young age group that is less prone to infection. In the new model, the age group 0 to 5 months is merged with the age group for 5 months to 5 years. The 65+ age group is split into an age group of 65 to 80 years and 80+ years. Older people with COVID-19 more commonly become very sick or die when infected. By splitting the age group, the model can give more insight into this occurrence.
The number of individuals per household is not available per municipality. However, it is available for the whole of the Netherlands. It is further assumed that the age groups 0 to 5 years, 5 to 12 years and 12 to 17 years all have a household. Of the age groups 23 to 35 years, 35 to 50 years and 50 to 65 years only a certain percentage has a household. Age groups 17 to 25 years, 65 to 80 years and 80+ years do not have households.

3.1.5 Commuter data

No school commuting data is available; therefore an estimation of school commuting is made. It is assumed that 5% of the age groups 12 to 17 travels to a neighbouring municipality for their secondary school for five days a week because children generally do not go to school further than one municipality from their home. This data is updated, because the following municipalities were missing: Heemstede, Meerssen, Opsterland, Reimerswaal, Rijswijk (ZH), Urk and Vlaardingen. The resulting network is shown on the left in Figure 10.
New job commuter data is not available; therefore, the data from 2013 is used. Travelling for jobs is done for five days a week because it is assumed people work five days a week on average.
From the check-ins and check-outs in public transport, the change in job commuting in 2020 during the COVID-19 outbreak is deduced (data: Translink, 2021). In Appendix B-1 and B-2, the data that is created manually is presented. It is assumed that people travel for their job on a weekday between 6 to 9 o’clock and 16 to 19 o’clock. It is also assumed that the reduction in commuting and travelling can be applied to the other modes of travelling, such as cars or bicycles.

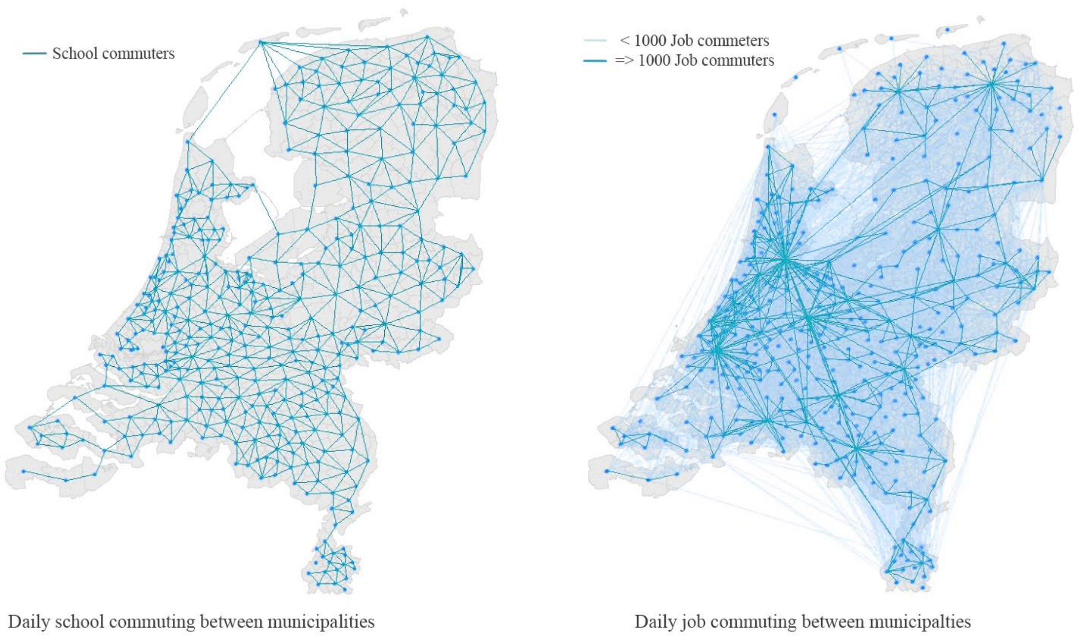

Figure 10. School and job commuting network (Tjalma, 2016).

3.1.6 Travel data

Holiday travelling

Holiday travelling is defined as an individual's movement to a place away from home for an extended period for leisure and recreation (own definition). In this thesis holiday travelling within the Netherlands by Dutch citizens is used, because the main focus lies on the Netherlands: external influences by incoming and outgoing foreign and domestic tourists would unnecessarily increase the complexity of the model, reducing the deductive value as it would become difficult to identify if a pattern is the result of external or internal influences.

Currently, municipality data on holiday travelling is lacking, but holiday travelling data for each province is available (Centraal Bureau voor de Statistiek, 2021): Figure 11 shows the number of tourists in each province. Since there is only province data, the number of tourists need to be realistically distributed between the municipalities in the destination province.

Considering the data, the easiest distribution would be to divide the number of tourists equally across all municipalities of a province based on the data from Centraal Bureau voor de Statistiek (2021). However, it is expected that this would lead to insufficient detail for the data to be of use in the model. Identifying a more realistic distribution would require extensive local research into tourism per municipality and as such lies outside the scope of this research. Therefore, it is decided to not include holiday travelling in the model.

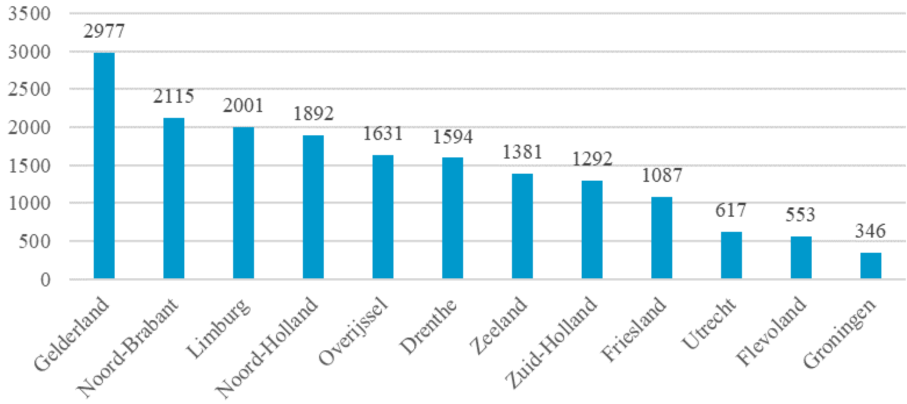

Figure 11. Holiday travelling to the Dutch provinces (x1000) in 2019 (data source: CBS[3], 2021).

Another, even more important, reason to not include holiday travelling in the model is that holiday travelling has little impact on the number of disease cases because of the measures taken by the government. There was a change in travel behaviour during the COVID-19 outbreak because many countries were not considered safe to travel to due to COVID-19 (Ministerie van Algemene Zaken, 2020b). Although people still went on vacations, several restrictions were implemented. For example, toilet blocks were no longer accessible, hotel restaurants were closed, and contact with people other than one's own travel group was not recommended (Ministerie van Algemene Zaken, 2020b). Furthermore, non-holiday related measures on shops, events, gatherings and the catering industry also impact the contact hours during the vacation (Ministerie van Algemene Zaken, 2020b). As many of these restrictions arise from other (non-holiday related) measures, it is assumed that few transmissions take place on holidays.

Gathering and event travelling

Gathering and event travelling (GAET) is defined as the travelling for recreational activities of at least one hour that are undertaken outside an individual's home municipality (based on CVTO definition Centraal Bureau voor de Statistiek, 2021). During GAET, individuals come into contact with other individuals, leading to the possibility of virus transmission. In this case, individuals can infect other individuals from the municipality they travel to, or they can get infected and bring the infection back to their home municipality.

There is a difference between leisure activities and visiting gatherings and events: not all of the leisure activities in Figure 12 belong to GAET. Each year there are around 3.562 billion leisure activities in the Netherlands (Centraal Bureau voor de Statistiek, 2021) (Figure 12). According to CBS, 40% of these activities take place at the home-municipality of the individual participating in the activity and therefore 60% take place outside the home municipality. The municipalities outside the home municipality are either neighbouring or non-neighbouring municipality. It is assumed that transmission does not occur during outdoor recreation because the virus does not transmit outside very well (Morawska & Milton, 2020).

Therefore, there are around 2.636 billion gathering and event activities a year, of which 1.582 billion require travelling outside of the home municipality.

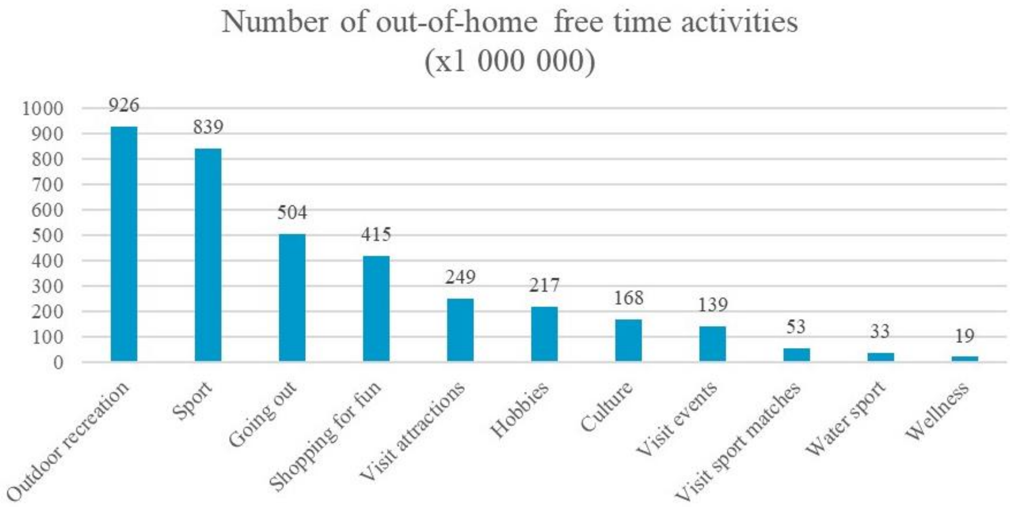

Figure 12. Number of leisure activities (x 1 000 000) in 2018 in the Netherlands (data source: CBS[3], 2021).

It is assumed that of the GAET group, 60% travels to a neighbouring municipality for a leisure activity, and 40% travels to a non-neighbouring municipality. From Table 3 it can be concluded that the individuals in the age groups of 0 to 5 years and 74+ participate on average 20% less in the different leisure activities compared to the other age groups (Centraal Bureau voor de Statistiek, 2021).

Out-of-home leisure Activity	0-5 yrs	6-12 yrs	13-17 yrs	18-24 yrs	25-34 yrs	35-44 yrs	45-54 yrs	55-64 yrs	65-74 yrs	>74 yrs
Outdoor recreation	90	91	85	80	92	92	92	88	84	79
Going out	70	79	86	91	95	93	89	87	84	84
Shopping for fun	73	74	78	79	87	87	83	80	83	76
Visit attraction	94	96	87	77	85	89	72	75	70	49
Culture	46	86	86	80	81	82	75	74	60	47
Visit events	45	65	73	74	72	75	71	72	64	56
Sport and sport related recreation	47	88	88	71	75	74	61	53	48	44
Hobbies	18	47	51	31	36	31	32	28	28	34
Visit sport matches	11	27	29	26	26	30	26	19	16	11
Water sport	12	30	36	20	21	19	16	15	13	3
Wellness	1	1	6	17	34	27	24	20	12	7
AVERAGE	41,7	59,3	62	56,6	61,2	60,7	54,9	52,3	47,8	41,1

Table 3. Participation in out-of-home leisure activities by age group in 2018 (data source: CBS[3], 2021).

Because the model includes 396 municipalities and each municipality can travel to one of the other 395 municipalities, 156 420 links between the municipalities were created as travel routes for the visit travellers. Since the inclusion of such a high number of links creates long loading times (~10 mins) and a slowly working model, only the links for job commuting are used to simulate GAET. To simulate travelling to neighbouring and non-neighbouring municipalities the data in the job commuting file is split into neighbouring and non-neighbouring municipalities with Excel. This allows the model to give separate values to the neighbouring and non-neighbouring municipality links.

Visit travelling

Visit Travelling (VT) is defined in this thesis as the travelling by an individual to friends or family members in another municipality (i.e. not their home-municipality) (own definition). From the check-ins and check-outs in public transport, the change in visit travelling in 2020 during the COVID-19 outbreak was deduced (data source: Translink, 2021). In Appendix B-1 and B-2, the manually created data is presented, for which it was assumed that people travelled for their job on a weekday between 6 to 9 o'clock and 16 to 19 o'clock. When individuals travelled during the hours before, in between, or after the work commute time slots and in the weekend, the travelling was taken to be a result GAET. It is assumed that the reduction in travelling and commuting can also be applied to other modes of travelling, such as cars or bicycles.

This kind of travelling encounters the same problem of increased computation time as the inclusion of visit travelling, therefore again the job commuting links are used (Figure 10), which reduce the links significantly. The job commuting links are split up into neighbouring and non-neighbouring links, as the travelling differs between neighbouring and non-neighbouring municipalities. Based on the survey answers, a table could be created in which the reduction and increase in visit travelling for each age group compared to job commuting is presented, which is done in section 4.2.

Survey visit travelling

There was no data available on visit travelling defined in this form; therefore, a survey was performed to gain the missing travel behaviour data relating VT to neighbouring and non-neighbouring municipalities. The survey was made with Google Forms since this is easily accessible software that is well suited and frequently used for surveying purposes. The survey is included in Appendix C-1. Besides questions about the age, sex and home situation of the respondents, the respondents were also asked how often they travelled to family and friends and neighbouring or non-neighbouring municipalities each month before and during the lockdown. Among the final questions, the respondents were asked to explain their reasons for travelling during the pandemic and the differences in their travel behaviour choices during the two different lockdowns in 2020 and 2021. The respondent had an option, in the end, to fill in any extra comments and recommendations. The survey was also given an option to fill in the travel behaviour of a child younger than 12 years because children of that age group are less likely to fill in such a survey on their own. This survey was shared via Facebook, WhatsApp groups and e-mail. Since elderly people (80+) can be assumed to use computers and mobile phones less often, a few were contacted and guided through the process. Eventually, the results were processed in Excel (Section 4.1).

3.1.7 Contact matrix

The contact matrices are created by the contact duration (T_{ij}) and the contact rate (γ_{ij}). They both are already provided in the thesis of Tjalma (2016), this data can be reused with minor modifications for this research. Both the contact rates and contact hours of Tjalma (2016) show that most contact is between the same ages and a relatively higher number of contact hours and contact rates for parents and children. They show a similar pattern, except for the contact/infection between age groups to 17, because children are less susceptible to COVID-19. Therefore the σ in the age group 0 to 5 months, 5 months to 4 years, 5 to 11 years and 12 to 17 years, should be lowered based on the graph by (Rijksinstituut voor Volksgezondheid en Milieu, 2020d) (Figure 5), but in this case, it is easier to just adjust the transmission rate in the model. The contact matrices can be reused for the COVID-19 model. When new measures are applied, the contact hours between age groups can be lowered in the contact matrix or the model. In the scenarios, multiple contact matrices are used, with different contact hours and the mean number of transmission events per hour of contact between fully infectious individuals and fully susceptible individuals (σ). The rates can be calculated with the following formula:

(1) $$P_{ij} = 1 - e^{-\sigma T_{ij}}$$
$$\beta_{ij} = \gamma_{ij} \times P_{ij}$$

P_{ij} = =The probability of transmission

e = Euler's number e ≈ 2.71828

σ = The mean number of transmission events per hour of contact between fully infectious individuals and fully susceptible individuals *

T_{ij} = Mean duration of contacts between an individual in age group i with people in age group j *

β_{ij} = The rate of disease transmission between a susceptible individual in age i with people in age j

γ_{ij} = The average number of individuals in age category j that is being contacted by one individual in age category i during one day, divided by the total population in age category j

(Del Valle et al., 2007; Tjalma, 2016)

* A reduction of 50% on σ or a reduction of 50% on T_{ij} has the same effect on the contact matrix.

The distance over which pertussis can be transmitted is 1 meter. As there is not a lot known yet about the transmission of COVID-19 and it is suspected to be around 1 meter based on the 1.5-meter distance rule (Ministerie van Algemene Zaken, 2020c), this data is kept the same.

3.1.8 COVID-19 data

Most COVID-19 data is available on the RIVM website. For each municipality, the data includes the new cases, the number of hospitalized individuals and the number of deceased individuals. Unfortunately, the data does not contain the age of the infected individual, which is only available per GGD region. The IC beds availability and the reproduction number are nationwide and fortunately, specific data on the availability and the total number of IC beds and hospital beds became public in 2021 and contains data about 2020. Before that, the data was only available for health professionals. Since May 2020, the IC-beds distribution is controlled centrally (Ministerie van Volksgezondheid, Welzijn en Sport, 2020b), therefore the usage of data on the nationwide level instead of on the municipality level is no problem.

The existing COVID-19 data is not always very reliable. The indicated number of infected depends on the number of tests done. However, since not every citizen makes an appointment for a test if they have symptoms, many infected individuals remain undiagnosed. The number of infected individuals also depends on the GGDs, who do not always deliver correct data and also often deliver it with a delay. This also applies to the hospitals and the number of deceased and IC-beds available. Compared to these numbers, the reproduction number is the most reliable. Still, the reproduction number is corrected by the RIVM and never 100% reliable.

Besides the reproduction number, the hospitalizations are used in this research. The number of hospitalizations is an important value on which the government often base their decisions because the health care system cannot handle too many patients at once. Over-crowded hospitals could lead to pressure on other departments in the health care in the Netherlands, putting even more people at risk.

For this research, it is still important to know roughly how many tests are done and how

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many of these are positive per 10 000 citizens because measures implemented by the government are often based on these numbers. Of the COVID-19 cases, 20% are asymptomatic throughout infection according to Buitrago-Garcia et al. (2020). These individuals are not aware they carry the virus because they do not have symptoms. For this research, it can be assumed that these are the people who do not take a test. Although the number of people not taking a test is probably higher because there are people who deny or ignore having symptoms. The RIVM states on their website that at the moment (20-12-2020) only 44% take a test when having symptoms (Ministerie van Volksgezondheid, Welzijn en Sport, 2020d). Of the group taking tests around 10.5% are positive in the months June to December 2020. Hence, during this research, it is assumed that 10.5% of the tests are positive.

3.1.9 Risk perception and coping appraisal data

The COVID-19 data is used to measure the risk perception of the national government and the municipalities. The risk perception depends on how the government perceives the severity and probability of an infectious disease. If the number of IC and hospital beds available is very low, then this will have a substantial impact on the risk perception of the government. The number of infected, the number of IC, hospital beds available and the R_0 all have an impact on the risk perception.

In the model, there are five categories identified on which measures can be implemented to lower the number of infected individuals: contact (matrix), job commuting, school commuting, GAET and VT.

Before it is possible to implement measures on these categories, it must be identified how much these variables should be lowered if measures are implemented. With the help of Translink (2021) data, a survey and the free time report from 2020 (Centraal Bureau voor de Statistiek, 2021) the reduction in job commuting, GAET and VT can be calculated during the lockdowns in 2020 by looking at the peak hours and off-peak hours of traffic and comparing these with the pre-lockdown numbers. For the contact (matrix) category, the effect of measures is derived from the variation of contact hours in the COVID-19 model as explained in section 3.1.7. As a result, data is obtained for all five categories for when there are no measures taken and when all possible measures are taken (a full lockdown). Since it is possible to have different levels of measures taken for different categories, there are many possible states between a full lockdown and when there are no measures taken at all. Hence different risk levels are defined per category. The measures taken for each category depend on the risk level perceived by the government for that category. When a category is at its lowest risk level, no measures are taken, while at its highest risk level, the measures taken result in a maximal reduction of that category. Depending on the category, intermediate-risk levels can be defined. It should be noted that at the highest risk level, a category need not be reduced to zero, e.g., at the highest risk level for job commuting, still some job commuting will occur. The risk levels for different categories can vary: for example, if job commuting is seen as a high-risk endeavour, the risk level for job commuting can be high while at the same time the risk level for school commuting can be low, or vice versa.

For school commuting, only two options are taken into account: all schools are fully open (normal school commuting) or all schools are fully closed (no school commuting). The measures taken for the category of school commuting depend on the risk level perceived by the government, which, for school commuting, can be either high or low. A high-risk level for school commuting results in measures taken to reduce school commuting, in this case, the closing of all schools until the risk level becomes low enough for schools to open again. As a

result, two risk levels are identified for school commuting.
For the categories of contact (matrix), job commuting, GAET and VT, 5 different risk levels are identified: the lowest risk level corresponds to no measures being taken for that category, while the highest risk level corresponds to measures for that category that corresponds to a full lockdown. The intermediate levels are distributed proportionally between the highest and lowest risk levels. Taking job commuting as an example, at the lowest risk level there are no restrictions on job commuting, resulting in regular job commuting (100%). At risk level 2 there are some restrictions and job commuting is at 80%. At risk level 3, job commuting is at 60%; at risk level 4, job commuting is at 40%; and at the highest risk level job commuting is at only 20% (but not zero). The reductions per risk level vary per category. Which risk level is identified per category depends on the scenario: in one scenario certain numbers may lead to a risk level of 4 for job commuting, while the same numbers may lead to a risk level of 2 or 3 for job commuting in a different scenario. This is a consequence of different scenario's weighing measures differently: all the scenarios have their own way of choosing the risk levels. The three different scenarios are discussed in the next sections.

By iteratively running simulations and comparing these with the actual data, a base model was created which simulates the COVID-19 outbreak in 2020 in the Netherlands including the lockdowns. Based on the results of this model the three different scenarios are created and modified: the Roadmap scenario, the economic scenario and the age scenario.
The risk perception and coping appraisal data are implemented in a rule-based sub-model in Netlogo. A Rule-based approach was chosen over a machine learning approach because there is relatively little data available and it is easier to implement. This is done using mostly "ifelse"- and "if"-statements in Netlogo. The risk appraisal data is numerical, and the coping appraisal data is also numerical and influences the contact matrix, job commuting, school commuting, GAET and VT.

Roadmap scenario
The government has a "Routekaart" (in English: Roadmap) available which is updated frequently (Ministerie van Algemene Zaken, 2020f). This Roadmap contains the risk perception and coping appraisal of the government and maps the corona measures (coping appraisal) per risk level (risk perception). During the COVID-19 waves, the government often abandoned this Roadmap and chose to implement other measures. Still, it is a very useful guideline and for this thesis, the Roadmap of December 2020 is used. With the Roadmap, rules can be implemented in Netlogo based on the risk levels and measures identified by the government. The Roadmap scenario results will show what is to be expected if the government follows the Roadmap completely.

Economic scenario
The government often abandoned its previous plans and implemented other measures than initially proposed during the COVID-19 epidemic and there are several reasons for this. Some measures have a large economic impact and are therefore less desired. For example: If the government prioritizes the economy and has to choose between closing schools or closing elderly homes, it will close the elderly homes. If schools need to close, parents have to stay home and cannot work or work less, which impacts the economy. On the other hand, closing an elderly home does not have as much of an impact on the economy. As a result, a government that prioritizes the economy would be more quickly inclined to close elderly homes than schools. The economy is therefore motivation for the government to choose other measures.
In this thesis, the economic scenario's risk level is based on the risk level described in the

Roadmap. However, the order in which the five categories and their measure per risk level are implemented depends on the economic impact such a measure has. In the model, a measure could have an impact on one out of five categories (contact matrix, job commuting, school commuting, GAET and VT). The measures are rated based on their economic impact by the author. The categories will be given a number between 0 (no economic importance) and 10 (high economic importance) for the five risk levels. Eventually, when the scenario is executed in Netlogo and the second risk level is reached, the five measures with the least economic impact are implemented. If the third risk level is reached the ten measures with the least impact are implemented, then for the fourth risk level 15 measures and the fifth risk level 20 measures.

Age scenario

The government can also choose to focus on the age of the infected individuals within the Netherlands for risk perception and coping appraisal. If, for example, the group of 17 to 25 has a large number of infected individuals, it is more logical to close clubs and bars, than museums and elderly homes. Although closing elderly homes would work, because the age 17 to 25 group with the most infections cannot visit the elderly and cause new infections. Still, this is a less obvious choice when trying to address the younger age groups. At the same time, closing bars and clubs will not affect the children till 17 and the elderly above 65 or 80, as they are less likely to visit such places in the first place. As closing bars and clubs is very specific and therefore difficult to process in the model the five categories (contact matrix, job commuting, school commuting, GAET and VT) are rated based on their impact on the age groups. To create a rating the model is run for the five categories to see how each category impacts the different age groups. Thereafter, if an age group has too many infected individuals, age group-specific measures are implemented, which will lower the number of infected individuals in those age groups.

For the user of the model, it is possible to select a scenario and the way the government perceives and deals with the risk with a dropdown menu in the interface. The moment in time when the government will take action by implementing measures depends on the rules stated in the Netlogo code. For example: if there are 100 infected individuals per 100 000 inhabitants, new measures are implemented. How the government takes action is implemented by lowering or increasing the contact matrix, job commuting, school commuting, GAET and VT. Additionally, it is possible to select three scenarios: the Roadmap scenario, the economic scenario and the age scenario. Each of these scenarios has other rules and order in its measures.

When new measures are introduced, the number of infected individuals will decrease or increase less. Different measures have different decrease rates. It is difficult to check the impact of one measure alone because often multiple measures are implemented. Research is necessary to calculate how much the contact matrix should be lowered when new measures are introduced. This data is obtained through calibration. Furthermore, the commuting can be stopped or adjusted in the model its interface, which can help to indicate that schools are closed, and people are working from home.

3.1.10 Source data

Table 3 shows the datasets from the previous model and the new datasets which are used during the research, these are also listed in Chapter 10. The old datasets are only changed to new datasets if there is time. It is assumed that the data from 2013 and 2019 are not very

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different.

Data	Source	Year	Level	New	New data available	Type of data after adaptions
Municipal data geographic	PDOK	2020	Municipality	No	Yes	Geographical: Vector/Point
GGD locations/regions	RIVM[1]	2020	GGD region	No	No	Geographical: Vector
Number of citizens per municipality	CBS[1]	2020	Municipality	No	Yes	Numerical
Age groups in population	CBS[1]	2020	Municipality	No	Yes	Numerical
Percentage households in population	CBS[2]	2020	National	No	Yes	Percentage
Job commuter data	CBS[3]	2013	National	No	No	Numerical
COVID- 19 Vaccination rate	-	2021	-	Yes	Yes	Numerical
Contact rates	Tjalma (2016)	Unknown	Population	No	No	Numerical
Contact duration	Literature (Del Valle et al., 2007)	2007	Population	No	No	Numerical
COVID-19 infected	RIVM[2]	2020	Municipality	Yes	Yes	Numerical
COVID-19 Hospitalized	RIVM[2]	2020	Municipality	Yes	Yes	Numerical
COVID-19 deceased	RIVM[2]	2020	Municipality	Yes	Yes	Numerical
COVID-19 age infected	RIVM[3]	2020	GGD region	Yes	Yes	Numerical
IC beds availability	Different sources	2020	National	Yes	Yes	Numerical
Reproduction number	RIVM[4]	2020	National	Yes	Yes	Numerical
Number of tests	RIVM[5]	2020	National	Yes	Yes	Numerical
Risk perception	COVID-19 data	2020	Municipality and National	Yes	Yes	Numerical
Risk perception and coping appraisal government	Ministerie van Volksgezondheid, Welzijn en Sport	2020c	National	Yes	Yes	Textual
Risk perception and coping appraisal government guideline	Ministerie van Algemene Zaken	2020e	National	Yes	Yes	Textual
Risk perception and coping appraisal municipalities	Different municipality websites	2020	Municipality	Yes	Yes	Textual
Number of checks ins and	Translink	2021	National	Yes	Yes	Numerical

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outs NS						
Number of free time activities	CBS[4]	2021	National	Yes	Yes	Numerical
Hospital bed occupation COVID-19	LCPS	2021	National	Yes	Yes	Numerical

Table 4. Data sources and information on the spatial level and the reuse of data from Tjalma (2016). See data reference and sources Chapter 9 and 10.

3.2 CONCEPTUAL MODEL & IMPLEMENTING VARIABLES

3.2.1 Updating existing model

An already existing model is used. This model is created in Netlogo, which is also used in this research to build the updated model. This model was created to research the effect of different vaccines scenarios on the reduction of pertussis. Afterwards, this model was changed to represent the diffusion of COVID-19 in the Netherlands. By implementing the factors representing the risk perception and coping appraisal, the model is used to answer the research question. Eventually, a rule-based sub-model in Netlogo is used to drive behaviour based on the collected data. This algorithm helps to predict measures taken by the government in relation to the reproduction number, number of infected individuals and availability of IC and hospital beds.

The model by Tjalma (2016) does need a few changes in the population groups. Gender and pregnancy are not necessary for the model and there are a few modifications in the age groups. The new model has 80 groups, which is 20 less than the model of Tjalma (2016). A lower number of groups makes the initial model run faster because fewer calculations need to be made. The population groups implemented by Tjalma are intertwined with the Netlogo code, which makes it hard to implement simple changes to the age. For this, a large part of the code had to be rewritten. Still, the old code was a useful guideline to do so. By rewriting the pertussis model with updated data and new age groups, the model was slowly transformed into a COVID-19 model. This was quite time consuming as all data had to be stored, managed, edited, analysed and integrated into the model again.

Since the model was already partly developed, some useful features already existed in the model. Features, such as ageing and job and school commuting were already included in the original model. The job and school commuting features are features that were not validated as Tjalma (2016) could also not validate them and it is deemed too time-consuming to do so for this research. Therefore, it is also decided to not validate GAET and VT due to the similarities in the process of validation.

Vaccination is a part of the model and is kept in the model because it is interesting for future COVID-19 research, but it is not a part of the scope of this thesis. Besides the existing agents in the model, which are the GGDs and the municipalities, another agent has added: the Netherlands as a whole. This agent is created by adding the data of all the municipalities together.

3.2.2 Conceptual model

By using the literature study and the data analysis, a conceptual model is created (Figure 14), which represents the development of the COVID-19 model. This conceptual model contains the factors that need to be included based on the results of the literature study and data analysis.

The conceptual model is based on the conceptual model of Tjalma (2016) and Abdulkareem et al. (2015). The conceptual model uses the Protection Motivation Theory (Rogers, 1975) to model the risk perception and coping appraisal. The nationwide threat appraisal is a result of different factors, such as the number of infected individuals, the number of tests, the total number of citizens in a hospital and the value of the reproduction rate. The risk perception arises from the threat appraisal. The Dutch government will judge the threats and decide if the risks are high enough to take new measures. Eventually, new decisions and actions can be taken during the coping appraisal phase. These measures are taken to lower the number of infected individuals (in certain age groups), citizens in the hospital, IC-bed availability and the reproduction number. The base model and the Protection Motivation Theory model influence each other: the actions taken during the coping appraisal affect the spread of COVID-19 and the spread of COVID-19 affects the risk perception and so on. In section 3.2.4 the rule-based sub-model is explained.

3.2.3 Population model

In Figure 13 the population model of a municipality is presented. The age groups are partly changed: The age groups 0 to 5 months and 5 months to 5 years are merged and the age groups 65+ is split in half. Although all the age groups participate in visit travelling and gathering and event travelling, not all the age groups participate in school and job commuting. School commuting can only participate in the age group 12 to 17 years and job commuting in the age groups 25 to 65 years.

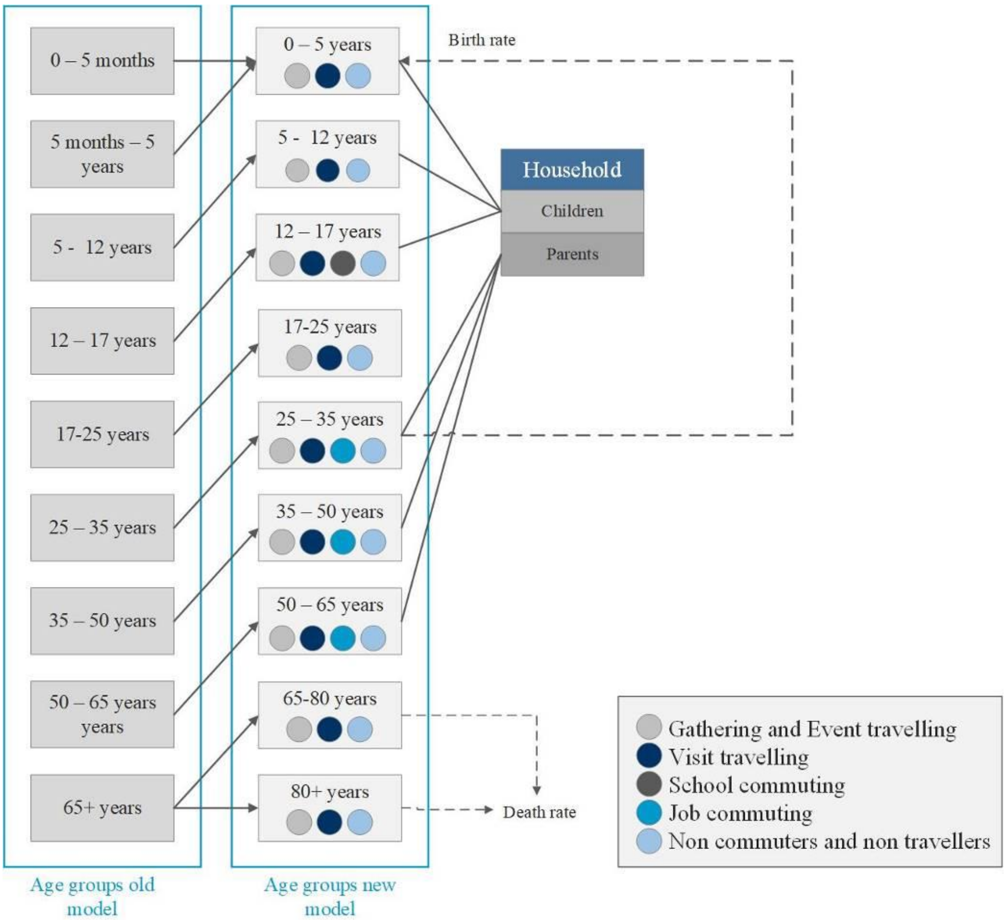

Figure 13. Population model of a Dutch municipality (based on Tjalma, 2016). note: in this thesis age groups include the lower bound but exclude the upper bound, i.e. 12-17 years means 12 ≤ age < 17 years.

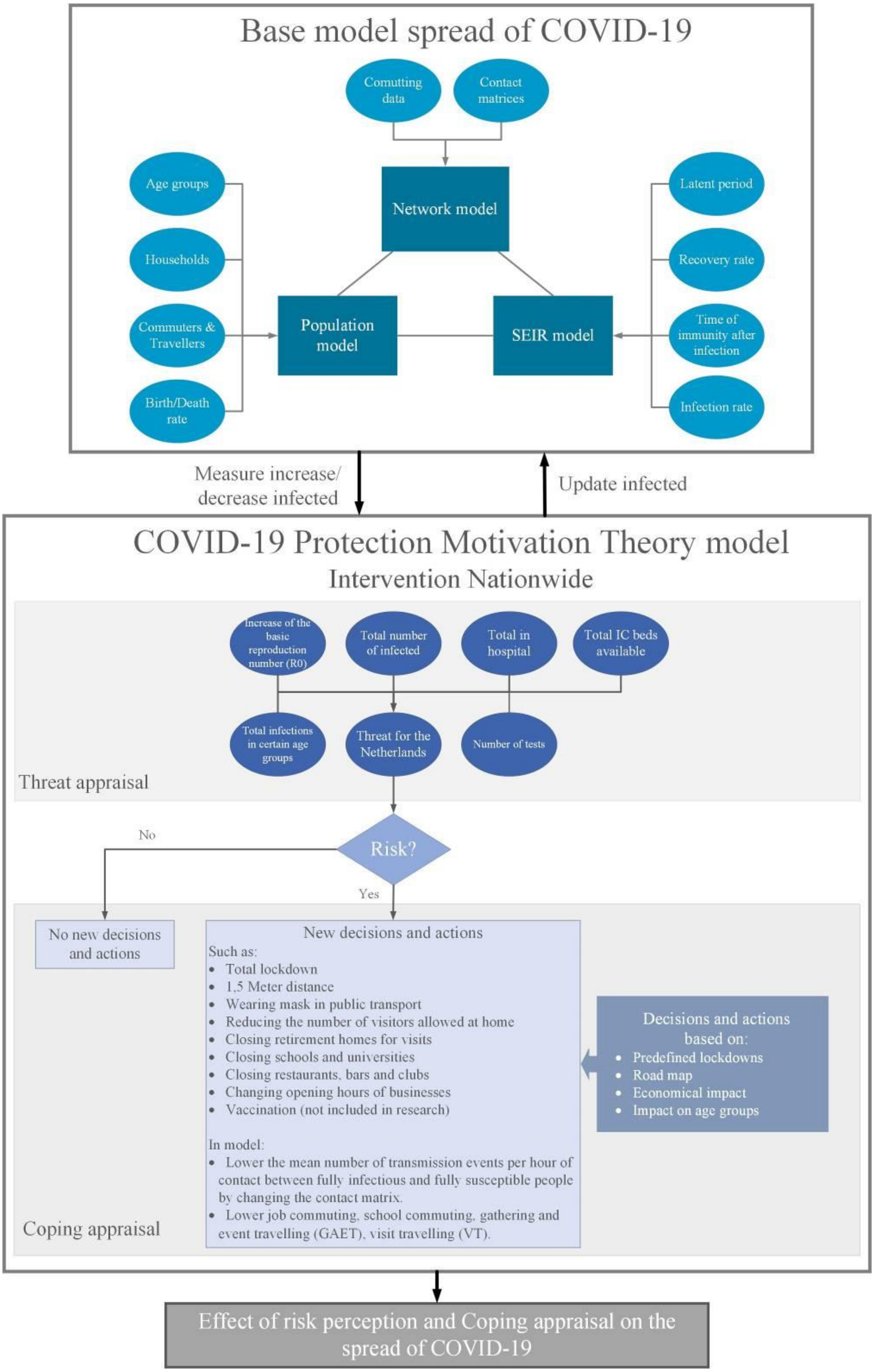

Figure 14. Conceptual model.

3.2.4 Rule-based sub-model

The rule-based sub-model is the new addition to the COVID-19 model. This rule-based sub-model focuses on the national measures, which the municipalities follow. The national government takes action when the total number of infected individuals, the number of IC and hospital beds occupied or the reproduction number in the Netherlands is high enough and risk is perceived. Then measures are taken, which all the municipalities will follow. Take into account that the national government will not take action if the number of infected individuals is concentrated in one area and also if the total number of infected individuals is too low to perceive a high enough risk on a national level. Implementing heavy measures has too much impact on the non-risk areas. Still, if an area relatively has a lot of infected individuals, something needs to be done.

Several scenarios are run in which the government needs to create a balance between several factors. At the moment two motivations are identified to choose certain measures. Therefore, three scenarios are run, including a scenario based on the Roadmap and a combination of economic and age:

1. Measures based on the Roadmap.
2. Economically justifiable measures.
3. Measures targeting age groups with high infection rates.

To create the data the existing measures are assessed on how much impact they have on the economy. Also, the impact of measures on age groups is assessed. Two tables are created. One to order the measures in the economic scenario and one to order the measures in the age group scenario. These are added to the rule-based sub-model. Subsequently, it is possible to select a scenario in the interface.

3.3 VERIFYING AND CALIBRATING THE AGENT-BASED MODEL

3.3.1 Verification

The model needs to be verified to show whether the model behaves as it is supposed to towards changes in the parameters in the model. Several simple experiments are formulated and tested (section 5.1). If all the experiments are successful then the behaviour of the model is as expected and the core functionalities work.

3.3.2 Sensitivity analysis

A sensitivity analysis tests how the model reacts to changes in parameters. The following parameter is tested: The transmission rate in the Netherlands (the mean number of transmission events per hour) for commuting and travelling separately and combined. It is expected that the partly unknown values of the transmission rate have a large impact on the behaviour of the model. The tested parameter is adjusted within a certain range, which is to be determined. There are no other parameters that directly link to the changes that are made.

3.3.3 Calibration

In the calibration, the parameters of the model are adjusted so that the model represents the COVID-19 diffusion in the Netherlands. The model is compared to data from the COVID-19 outbreak. In the calibration, the data about the number of infected individuals, the number of hospitalizations and the reproduction number in the Netherlands is used. For this research the following parameters are calibrated:

- The seasonal transmission rate.
- The age groups distribution.
- The infectious period.
- The day of the outbreak.

Calibration is done by running the model for a year and comparing the models' data to real-life COVID-19 data. It is important to use calibration carefully in this model since it is possible to over-calibrate.

3.4 ANALYSING RESULTS AND FINALIZING RESEARCH

3.4.1 Analysis of the results

Here the experiments to study the risk perception and coping appraisal in the Netherlands are conducted. The main focus of the research lies in the graphs of the model that is studied. The different scenarios must bring more insight into the influence of national government on their citizens. The patterns created by the model also can provide valuable information about these dynamics in the real world. The number of infected individuals and most other numerical COVID-19 data that is created is not as useful, because the displayed quantities and the source data are less reliable. The reproduction number (R_0) is one of the numbers which is focused on. This number is more reliable than the number of infected individuals because the number of infected individuals is hard to estimate accurately, resulting in the model often estimating it too high or too low compared with reality. On the other hand, the data available about the number of IC and hospital beds occupied is reliable because these numbers are well kept by trustworthy sources. Still, it must be taken into account that the hospitalizations were relatively higher in this dataset at the start of the virus outbreak because there was less knowledge about the treatment of COVID-19 patients. The reproduction number in combination with the hospitalizations are useful to determine the intensity of the measures needed to prevent further spread of the virus.

3.4.2 Finalizing research

In the discussion, the problems encountered during the research are discussed. In the conclusion, the research questions are answered and afterwards, recommendations for future research are made.

4. DATA COLLECTION AND ANALYSIS

In this chapter, the data collection and analysis are presented. This research makes use of data from various data sources and required adjustments to the data before its use. Therefore in this chapter, it is described where the data is found, how the data is used and which changes were necessary. In section 4.1 the calculations of the age groups participating in GAET is explained. In section 4.2 the VT survey answers are discussed and processed into usable data. In section 4.3 the calculation of the number of hospitalizations and the number of COVID-19 tests based on data of the RIVM is presented.

4.1 GAET TRAVELLING

From GAET 60% travels to a neighbouring municipality for a leisure activity, and 40% travels to a non-neighbouring municipality (Centraal Bureau voor de Statistiek, 2021). Since for GAET the job commuting links are used, an adjustment must be made. As a result, the job commuting file is split into neighbouring and non-neighbouring municipalities and the total number of travels is calculated. It is known that there are 2.636 billion travels a year and therefore 7.222 million a day. Based on this value split for neighbouring (4.333 million travels) and non-neighbouring municipalities (2.889 million travels) and the number of job commuting links a ratio is created. It is calculated that the job commuting links of the neighbouring municipalities must be a factor 1.6 times higher and for non-neighbouring municipalities, a factor 0.78 lower to represent GAET.
Table 3 proves that there is a difference in GAET in the age groups (Centraal Bureau voor de Statistiek, 2021). Based on this table and the number of individuals in the age groups Table 5 was created, which indicates the difference in GAET between age groups.

Age group	GAET share
0 to 5 years	0.76
5 to 12 years	1.09
12 to 17 years	1.14
17 to 25 years	1.04
25 to 35 years	1.12
35 to 50 years	1.08
50 to 65 years	0.97
65 to 80 and 80+ years	0.85

Table 5. Participation in GAET per age group (data source: CBS[3], 2021). Note: in this thesis age groups include the lower bound but exclude the upper bound, i.e. 12 to 17 years means 12 ≤ age < 17 years).

4.2 VISIT TRAVELLING

The survey was published on 20 January 2021 and the last answer was received on 5 February 2021 in Google forms. The survey was spread via Facebook, WhatsApp and e-mail and respondents close to the author (ages 25 to 30 years) were asked to share the survey with others, especially with parents and older family members (50+ years), as it was expected that there would be a low number of respondents in those age ranges. The survey was conducted in Dutch and the whole survey is shown in Appendix C-1.
The survey was filled in by 221 individuals. Of these individuals, the survey response of two

applicants did not meet the requirements because one respondent indicated that their home municipality was not in the Netherlands (Barcelona) and from the answers of the second respondent it could be deduced that the questions were not interpreted correctly and hence these answers were not considered in the processing of the survey data. Three surveys were submitted two times and the duplicates had to be removed. As a result, five surveys were removed; hence 216 surveys were used for the research.

4.2.1 Processing answers

Most adjustments to the survey answers were to the questions about how often the respondents visited other municipalities or within the home municipality. To make this data useable in Excel a few adjustments were necessary, such as removing additional characters (2x = 2, 5 keer = 5). If a respondent answered "N.v.t." (does not apply), "niet" (not) or "geen familie of vrienden in aangrenzende gemeenten" (no family and friends in nearby municipalities) to the travel questions the number of travels is set to zero for that question. Some respondents did not have a clear answer and stated that their travel behaviour is "between seven to ten times", in these cases the number in between is taken (in case of the example: 8.5).

4.2.2 Survey results

The largest share of the respondents is female (73.6%) and thereafter male (25.5%). Two respondents filled in that they rather not tell or that their sex is unspecified: one respondent would rather not tell their sex (0.5%) and one respondent filled in that their sex was unspecified (0.5%). In Figure 15 the number of respondents per age group is presented. This figure shows that the largest group of respondents are between the ages 25 to 35 (31.3%), the second-largest between the ages 50 to 64 (27.8%) and afterwards the ages 17 to 25 (19.6%). The large share of female respondents and 17 to 35-year-old respondents were likely a result of the more widespread use of Facebook among females and students who fit the profile of the author.

In Figure 16 the municipality where the respondents live is presented. The respondents are spread over the country but many live in the municipality Groningen, Oldambt or the Randstad (Amsterdam, The Hague, Rotterdam). This is due to the social network of the author and the subsequent spread of the survey via said social network. It is also known that the survey was shared on Facebook by a respondent from Oldambt and a respondent from Alblasserdam, which also explains the high number of respondents in these areas.

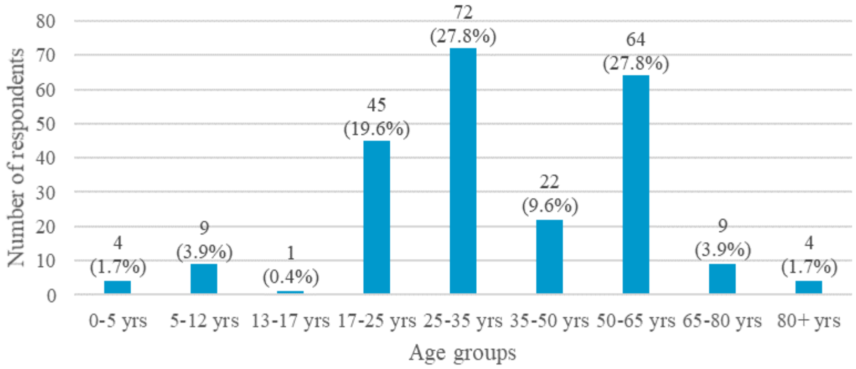

Figure 15. Age respondents survey (216 respondents and 230 answers, includes respondents answering for their children). Note: in this thesis age groups include the lower bound but exclude the upper bound, i.e. 12-17 years means 12 ≤ age < 17 years).

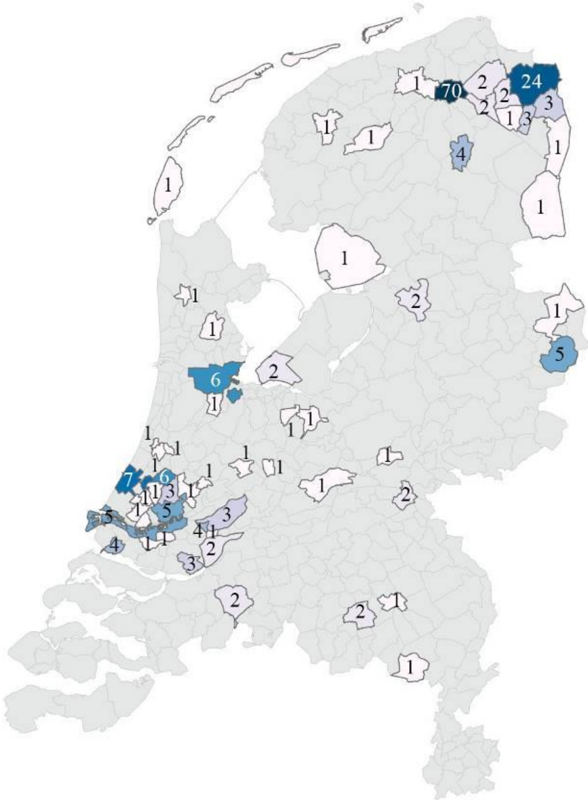

Figure 16. The home municipality of the survey respondents (216 respondents). The number in the municipality indicates the number of respondents living in that municipality. The darker the colour of the municipality the more respondents live there.

Households

The household of the respondents is derived from the number of individuals and the ages of the individuals they live with (Figure 17). It is assumed that children below the age of 17 still live at home and that individuals above 30 years of age that live together are partners. The individuals between 17 and 30 years are either housemates or partners if they have a two-person household. If more than two individuals are living on an address of the ages 17 to 30 it is assumed that the residents are housemates. With an age gap of 18 years or more between the individuals in the household, it is assumed that these individuals have a parent/child relationship. There is a nice distribution over the several identified households. Five are set to unknown as the number of people in the household and the number of the ages entered in the survey did not match.

Travel behaviour

Figure 18 the difference in travel behaviour between the first and second lockdown is presented. It shows that for most people there is no difference in travel behaviour when comparing the two lockdowns. The number of respondents travelling less and travelling more in the second lockdown is roughly equal and therefore it can be concluded that the number of visit travels should not have changed noticeably in the second lockdown compared to the first lockdown.

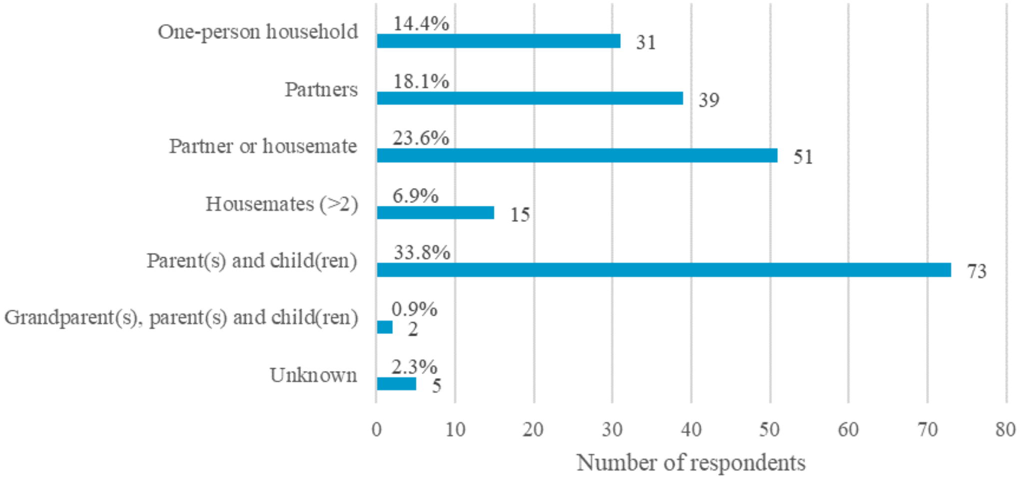

Figure 17. Home-situation respondents derived from the number of people in the household and ages of the people in the household (216 respondents).

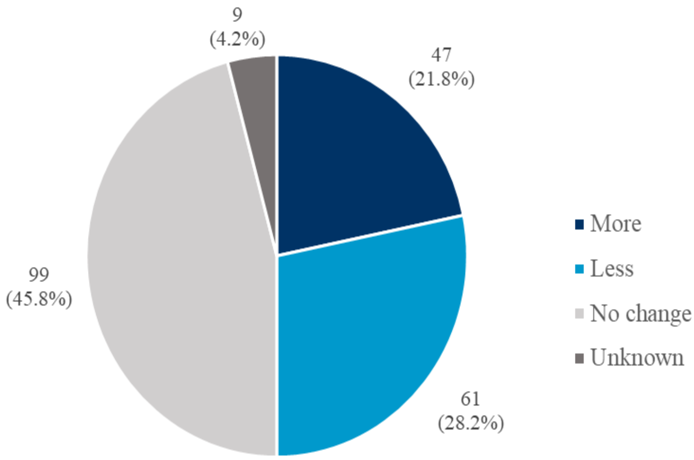

Figure 18. Change in travelling before and during lockdown respondents survey (216 respondents).

In Figure 19 the average number of travels in the home-municipality, to neighbouring municipalities and non-neighbouring municipalities each month per age group is presented. The figure shows that especially the younger age groups (5 to 25 years) travel mostly within their home-municipality. The same applies to the age group of 80+ years. A possible explanation for this could be that these age groups have more time on their hands and are more active overall, however, the underlying reason cannot be deduced from the survey. On the other hand, the age group of 50 to 65 years is the only age group that visit travels more to the neighbouring municipalities than their home-municipality before and during the lockdown.
Contrary to the other age groups, in the age groups 17 to 25 years and 65 to 80 years, travelling is more often done to non-neighbouring municipalities than neighbouring municipalities. It is assumed that the respondents in the age group 17 to 25 years are mostly students. As students often live in a city other than where their parents live, they must travel further to visit their parents and friends in their previous home-municipality. For the age group 65 to 80 it is not known why they travel more often to non-neighbouring municipalities.

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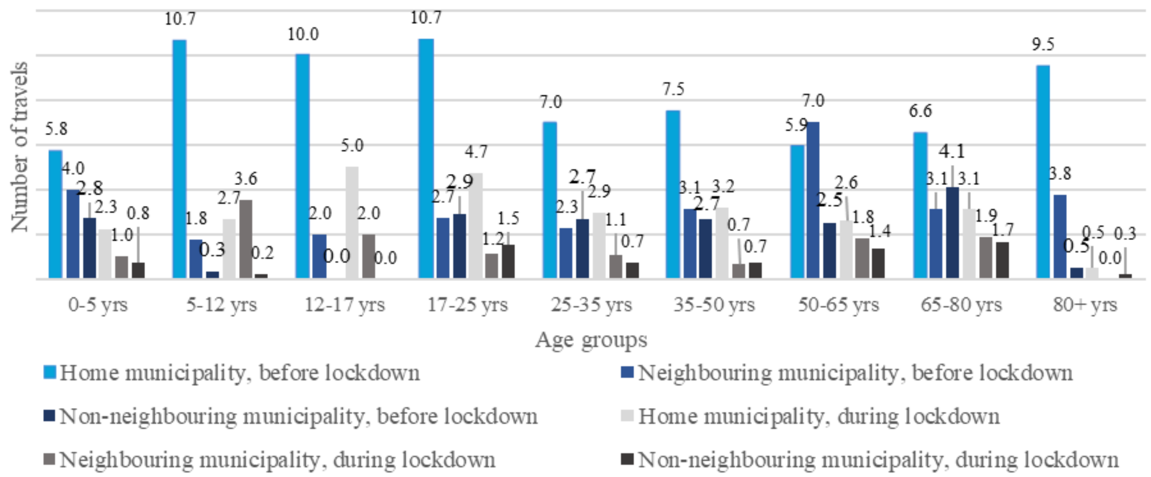

Figure 19. The average number of travels each month per age group (216 respondents and 230 answers, includes respondents answering for their children).

Figure 20 shows the percentage of travels done by the respondents during the lockdown compared to before the lockdown, consequently, a lower percentage means a higher reduction in travelling. All age groups have a relatively high reduction in visit travelling to neighbouring municipalities and a relatively low reduction in travelling within the municipality. The age group 50 to 65 years has the lowest reduction of visit travelling compared to all the other age groups, which is interesting as they are more likely to get very sick if they get infected and it would be more logical if they were to take action by reducing their number of visits to reduce the chance of infection. Another interesting result indicated by the survey data is that the reduction in travelling is relatively low for the age group 65 to 80, which is a risk group. The age groups 5 to 12 years and 12 to 17 years have a large reduction, this could be the results of the schools being closed, leading to a decrease in the chance for children to meet other children.
To convert the job commuting links to VT links, numbers need to be obtained by comparing the number of job commuting links with the number of VT links per age group deduced from the survey (Table 6). The numbers, without a unit, represent VT per age group, for neighbouring and non-neighbouring municipalities, before and during a lockdown. Multiplying the numbers in the table with the job commuting links for either neighbouring or non-neighbouring municipalities results in the new value representing the VT for the selected age group. This table is used in Netlogo to simulate VT per age group for neighbouring as well as non-neighbouring municipalities before or during a lockdown.

Age group	Neighboring no lockdown	Non-neighboring no lockdown	Neighboring lockdown	Non-neighboring lockdown
0 to 5 years	1.1	1.1	0.7	0.8
5 to 12 years	0.5	0.1	2.4	0.2
12 to 17 years	0.5	0.0	1.3	0.0
17 to 25 years	0.7	1.2	0.8	1.5
25 to 35 years	0.6	1.1	0.7	0.7
35 to 50 years	0.8	1.1	0.5	0.7
50 to 65 years	1.9	1.0	1.2	1.4
65 to 80 and 80+ years	0.9	1.3	1.0	1.5

Table 6. Visit travelling behaviour per age group (based on the survey).

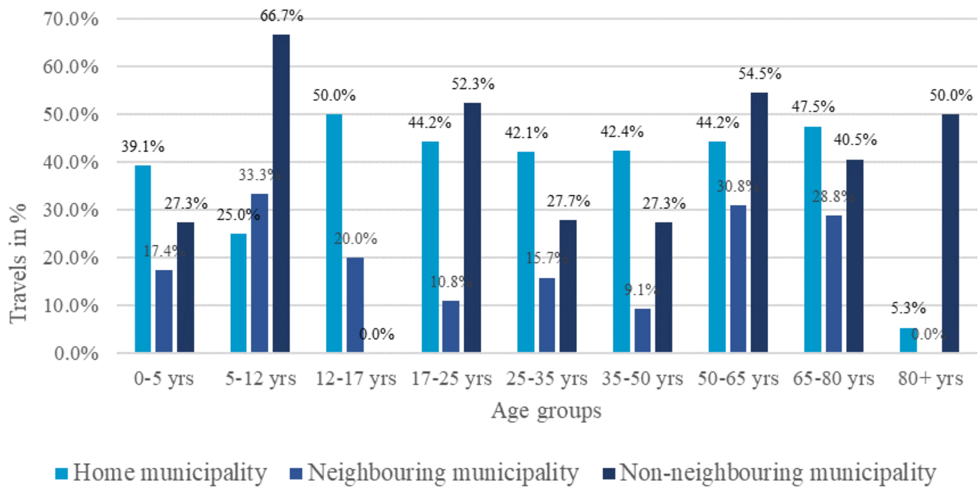

Figure 20. Visit travelling before and after a lockdown compared in percent (216 respondents and 230 answers, includes respondents answering for their children).

Explanations respondents
The respondents had the opportunity to explain the answers. The respondents' choices to go to a family member or friend were based on several considerations according to the answers from the survey:

- ✓ Age of person whom they visit;
- ✓ The health of the person whom they visit;
- ✓ How important the relationship between the visitor and the person they visit is (emotionally);
- ✓ How nearby the person they want to visit lives (geographically);
- ✓ The urgency of visit (e.g. informal care, help with administration);
- ✓ The need for social contact (e.g. someone who is living alone, visiting the grandchildren);
- ✓ A special event (e.g. birthday or deceased family member);
- ✓ The number of infected as stated by the RIVM (e.g. if there are many new cases, they more often decide to stay at home).

How the respondent weighed whether to go or not differs per respondent. For example, one respondent would visit purely because they needed social contact while another respondent would stay home and would only leave to take care of a family member.
The main reason for choosing not to visit someone was because of the fear of infecting and/or losing a family member or a friend, especially older family members or friends. Multiple respondents indicated that they are cautious when visiting a family member or friend, hence to reduce the number of people they meet they only come together with a select group of close family members and friends. One respondent indicated that she would not travel far away and stays home as much as possible.

4.3 TESTS AND HOSPITALIZATION

4.3.1 Tests

The number of tests taken is based on the number of infected, the infectious period and the number of asymptomatic individuals. The number of tests and the number of positive tests from June to December 2020 are used to identify the relationship between the two. These months are chosen because there is data available of these months as the national test facilities and tracking system was finally finished and in use (Ministerie van Algemene Zaken, 2020d). In these weeks the number of positive tests was 10.5% of the total number of tests taken (data source: RIVM[6], 2021). It is assumed that 20% of the COVID-19 cases are asymptomatic (Buitrago-Garcia et al., 2020). Therefore the following formula can be used to calculate the number of tests using the total number of infected:

$$\text{(2)} \quad Nr\ of\ tests = \frac{Total\ infected \times (1 - Proportion\ asymptomatic)}{Duration{-}of{-}infectivity \times Proportion\ positive\ tests\ week\ 23\ till\ 53} \times 100$$

And the following to calculate the number of positive tests:

$$\text{(3)} \quad Nr\ of\ positive\ tests = \frac{Total\ infected \times (1 - Proportion\ asymptomatic)}{Duration - of - infectivity}$$

4.3.2 Hospitalization

The hospitalizations are based on the number of hospital admissions in 2020 as indicated by the Rijksinstituut voor Volksgezondheid en Milieu (Data source: RIVM[3], 2020). The RIVM kept up the number of infected and if they were hospitalized and/or deceased due to COVID-19. Together with the age of the infected, it is possible to calculate the chance a person of a certain age gets hospitalized. It is assumed that asymptomatic individuals do not count as potential hospitalized individuals, therefore 20%, the percentage that is asymptomatic according to Buitrago-Garcia et al. (2020) is subtracted from the number of infected. The results are visible in Table 7 and the chance to get hospitalized are especially high for the age groups of 65 till 80 years and 80+ years. This is as expected as these age groups belong to the risk groups for COVID-19 because people of these ages often have poor health and underlying health conditions (Clark et al., 2020). The number of hospitalizations is also relatively high for the age groups 0 till 5 and 5 to 12 years. This is probably because the infection in this age group is less often detected (Gudbjartsson et al., 2020; Heavey et al., 2020; Jiehao et al., 2020). After all, children usually have only mild symptoms (Jiehao et al., 2020) and are not the drivers of transmission (Heavey et al., 2020), therefore many infected children are not detected. Since the number of children infected in the model is set low it is expected that the higher chance to get in the hospital for children will not have a lot of effect on the number of hospitalisations.

Age group	Chance to get hospitalized
0 to 5 years	0.0202
5 to 12 years	0.0104
12 to 17 years	0.0008
17 to 25 years	0.0015
25 to 35 years	0.0039
35 to 50 years	0.0097
50 to 65 years	0.0386
65 to 80 years	0.0849
80 plus years	0.0944

Table 7. The chance to get hospitalized per age group (data source: RIVM [3], 2020). note: in this thesis age groups include the lower bound but exclude the upper bound, i.e. 12 to 17 years means 12 ≤ age < 17 years).

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5. VERIFICATION, SENSITIVITY ANALYSIS AND CALIBRATION

Before the model can be used to reach conclusions, the model must first be verified and calibrated. Therefore, in this chapter, verification (5.1) and calibration (5.4) are discussed and executed. Besides verification, a stability check (5.2) and a sensitivity analysis are conducted (5.3). During the verification, one checks whether the system has been made according to the conceptual design. In the sensitivity analysis, experiments are conducted to see how sensitive the model is to changes in the parameters. In the sensitivity analysis, it is determined which variables need calibration. At the end of the chapter, the calibration is described and executed. In the calibration, the unknown input values are acquired. This can especially help with deciding the values of the most sensitive parameters and helps to evaluate the reliability of the results.

5.1 VERIFICATION

During the verification, one checks whether the system has been made according to the conceptual design. So, have all the requirements been processed? It cannot be expected that the model output is the same as reality, but similarities in patterns are necessary to call the model a good fit. Calibration can help to enhance the fit of the model. During the verification experiments on travelling, lockdowns and contact matrices were used. In the end, the results of the verification are presented.

To verify this model eight experiments are formulated. These are used to check if the models' behaviour to changes of parameters is as expected. The following experiments are executed:

5.1 Travelling

Two new types of travelling are added, this research will verify that this travelling works properly.

- ✓ The disease does not spread to other municipalities if the commuting is turned off.
- ✓ The pattern of the infected individuals per municipality, which are visualised in maps, differs when the number of individuals commuting is higher or lower. It is expected that there will be spread to the neighbouring municipalities (expansion spread) as well as spread to large non-neighbouring municipalities (relocation spread) if either commuting or travelling is used in the run.
- ✓ If only gathering and event travelling (GAET) is switched on, the infected individuals in other municipalities, where the virus was not manually introduced, rise. This could eventually also result in a rise of infected individuals in the municipality where the virus is introduced by GAET from other municipalities.
- ✓ If only visit travelling (VT) is switched on, the infected individuals in other municipalities rise. This could eventually also result in a rise of infected individuals in the municipality where the virus is introduced by VT from other municipalities.
- ✓ If job commuting, school commuting, VT and GAET are combined the number of infected rises significantly compared to only VT and GAET. Moreover, the virus will spread faster within municipalities and across municipalities in the Netherlands.

5.2 Lockdowns

During the pandemic, two lockdowns were implemented by the government. This is simulated in the model and this research will verify if this works properly for the transmission rate, school commuting, job commuting, GAET and VT altogether. There are different reductions specified for different kinds of travelling or commuting.

- ✓ If lockdowns are implemented the graphs for that run will show a reduction in the number of infected in the first peak compared to graphs without a lockdown.
- ✓ If school commuting, job commuting, holiday travelling and GAET are all turned on and the lockdown periods are implemented, the patterns of the resulting map differ compared to a run with no lockdowns.

5.3 Change of contact matrix

In the initial model, there was just one contact matrix. In the new model, the contact matrix can change per age group when restrictions are implemented. To test if this works different contact matrices ratios are implemented during a run with the model.

- ✓ If school commuting, job commuting, holiday travelling and GAET are all turned on and the transmission rate is reduced with ratios for the age group younger than 25 years, 25 to 65 years and 65+ years the resulting graphs for hospitalization for the age groups differ depending on the implemented contact matrix.

5.1.1 Travelling

For travelling, the GAET and VT are going to be verified. For this verification, the whole of the Netherlands is experimented on within the model. In the next paragraph, the parameters used for the runs are determined.

To analyse the patterns in the maps created by the Netlogo model the pattern-oriented modelling (POM) strategy is used. This strategy attempts to make bottom-up modelling "rigorous and comprehensive" (Grimm et al., 2005, p. 1; Grimm & Railsback, 2005). In POM multiple patterns of maps are observed and explained in real systems in different levels and scales "to optimize model complexity and to reduce uncertainty" (Grimm et al., 2005, p. 1). In this sensitivity analysis, POM is used to analyse the spread of COVID-19 using, graphs, RIVM COVID-19 data and maps. Together with the processes of diffusion as described by Cliff et al. (1981) and Kuebart & Stabler (2020), the patterns can be analysed.

According to Hu et al. (2020) the infectious period for symptomatic patients is 9.5 days and for asymptomatic patients 6.0 days. Of the COVID-19 cases, 20% are asymptomatic throughout infection according to Buitrago-Garcia et al. (2020). The LCI assumes it is 6.0 days on average for an infected individual according to their guidelines (Rijksinstituut voor Volksgezondheid en Milieu, 2021). As there are various values, the infectious period will be calibrated in section 5.3. For now, the infectious period of 9 days is chosen.

The duration of immunity is more than eight months according to Dan et al. (2021). It seems that the duration of immunity is even longer, but no published research has proven this yet (on 26-01-2021). For this research, it is assumed that all infected remain immune until the end of 2020.

In the Netherlands, the first proven infection of COVID-19 was on 27 February 2020 (Ministerie van Algemene Zaken, 2020a). The virus started in the province of Brabant, and the celebration for Carnival had a great contribution to the spreading of the disease. From 26 February 2020 to 10 March 2020, there were 44 infected individuals in the municipality of Tilburg and around 250 infected individuals in the Netherlands (Rijksinstituut voor Volksgezondheid en Milieu, 2020b). At that time Tilburg had the largest share of the number of infected individuals. Although the first infected individual was on 27 February, it is expected that many were infected beforehand and for that reason, the model starts on 24 February 2020. There is no data available before 27 February, therefore the number of

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infected on 24 February 2020 needs to be calculated. With a serial interval of 5.4 (Rai et al., 2020) and an R_0 of around 2.0 (Data source: RIVM[4], 2020) the number of infected individuals on 24 February 2020 is calculated with the formula below.

(4) $$T_0 = t_2 - t_1$$

(5) $$I_{t_1} = I_{t_2} / R_0^{(T_0/S)}$$

$$T_0 = 55 - 70 = 15$$

$$I_{t_1} = 250/2^{(15/5.4)} = 24.8$$

T_0 = *Time interval*
I_{t_1} = *Number of infected individuals* t_1
I_{t_2} = *Number of infected individuals* t_2
R_0 = *Reproduction number*
S = *Serial interval*

This results in 25 infected individuals on 24 February 2020 in the Netherlands. Based on the previously mentioned data and the results of the formula it is decided to introduce 25 infected individuals in the municipality of Tilburg on day 55, 24 February 2020, with an infectious period of 9 days and a duration of immunity of 1 year. All parameter values are summed up in Table 8.

Parameter	Value	Adjusted value	Reference
Transmission rate	0.02 – 2.0	-	Sun et al. (2020); Del Valle et al. (2007)
Exposed period	5.4 days	6 days	Rai et al. (2020)
Infectious period	6 – 9 days	9 days	Hu et al. (2020); Rijksinstituut voor Volksgezondheid en Milieu (2021)
Recovered period	>8 months	1 year	Dan et al. (2021)
Number of infected asymptotic	20%	-	Buitrago-Garcia et al. (2020)
Number of infected introduced	25	-	Rijksinstituut voor Volksgezondheid en Milieu (2020b)
Start location	Tilburg	-	Rijksinstituut voor Volksgezondheid en Milieu (2020b)
Day outbreak	Day 32 – day 55	Day 55	Ministerie van Algemene Zaken (2020a)

Table 8. Parameters model.

Merow & Urban (2020) predict that the number of virus infections decrease during summer, rebound in autumn and peak in the winter, based on their research in the summer of 2020. Such a pattern is also visible in the number of positive tests in the Netherlands in 2020 (Figure 21). Therefore, the transmission rates have been set to seasonally change. It is also important to take into account that if the transmission rate is too low, the virus will not spread to other municipalities. Therefore, after several runs, a transmission rate is chosen which makes it possible for the virus to spread to other municipalities, but which does not spread too fast, which would lead to the whole of the Netherlands being infected in a short amount of time.

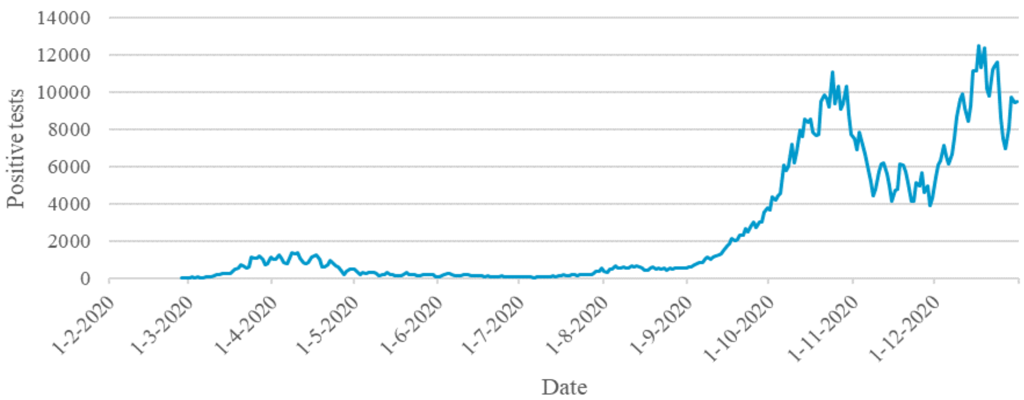

Figure 21. Number of positive tests in the Netherlands 2020 (data source: RIVM[6], 2021).

Eventually, the reproduction number in the Netherland in 2020 was compared to the reproduction number created by the Netlogo model for Tilburg. This reproduction number originally had a lot of small peaks, because of the weekly commuting and travelling calculations. Hence, the reproduction numbers resulting from the Netlogo model are calculated using a 7-day average in this thesis, which results in smoother graphs. The simulation in Netlogo does not yet include the lockdowns, commuting and travelling. In Figure 22 the comparison shows that with a transmission rate of 2.0 for winter, 1.0 for spring and autumn and 0.6 for summer relatively similar reproduction numbers compared to the reproduction number as calculated by the Rijksinstituut voor Volksgezondheid en Milieu (2020g) are created. The transmission rate in winter is based on the transmission rate of 2.2 identified by Sun et al. (2020). Although there are some differences in the reproduction number, especially in February and March 2020, this graph is a relatively close representation of the real reproduction number.

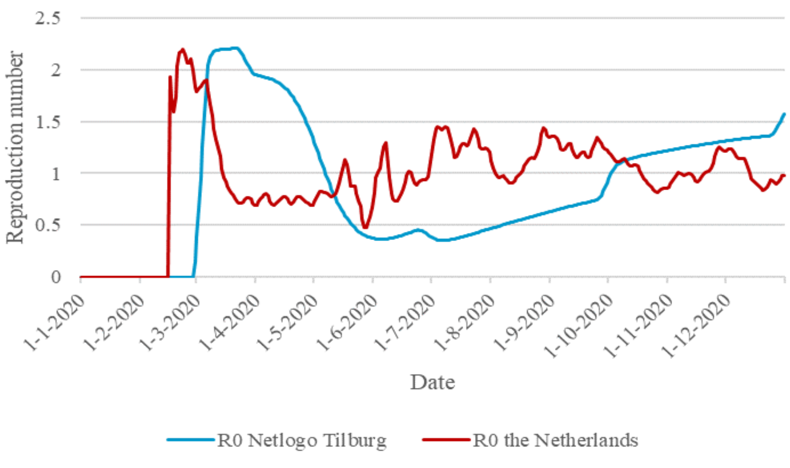

Figure 22. Reproduction number in Tilburg simulated in Netlogo compared to the real reproduction number in 2020 (data source: RIVM[4], 2021)

Gathering and event travelling

To verify gathering and event travelling (GAET), the only interaction between municipalities is taken to be a result of GAET, so this results in simulations without job commuting, school commuting and VT. Figure 23 shows that the reproduction number is especially high at the start; A possible explanation is the rise of infections in Tilburg itself, which is the flat area in the first half of March. The small peak in April 2020 is a result of the spread of the virus due to GAET.

In Figure 24 the peak of the reproduction number is before the peak in the number of infected individuals. The reproduction number indicates a rapidly increasing number of infected, which is visible in the graph as a delay in peaks between the number of infected individuals and the reproduction number.
The number of infected individuals and the spread in the Netherlands in 2020 can be seen in Figure 25. The number above the date of each map is the day in 2020 the map represents, of which day 1 represents 1 January 2020. The date below it corresponds with this number. Both the date and the number representing the day are used to make it easier for the reader to understand the time steps between each map. On day 70 (10 March 2020) only the municipality where the virus was introduced has infected individuals. On day 105, it is visible that the virus spread slowly to neighbouring municipalities (expansion spread) because of GAET and the number of infected is especially high in the surrounding municipalities (Figure 25). The higher percentage in the number of infected individuals in non-neighbouring municipalities is caused by relocation spread. On day 140 most local municipalities do not have any infected individuals anymore. This is caused by a larger number of commuters travelling between the larger municipalities and because large municipalities have more susceptible individuals, which causes the virus to never completely disappear. The peak of the epidemic is in May and in October and November, a new rise in the number of infected appears.

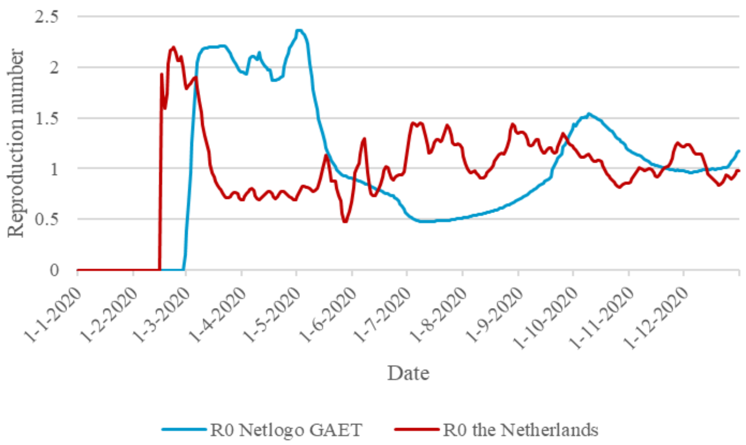

Figure 23. Reproduction number caused by GAET simulated in Netlogo compared to the real reproduction number in 2020 (data source: RIVM[4], 2021).

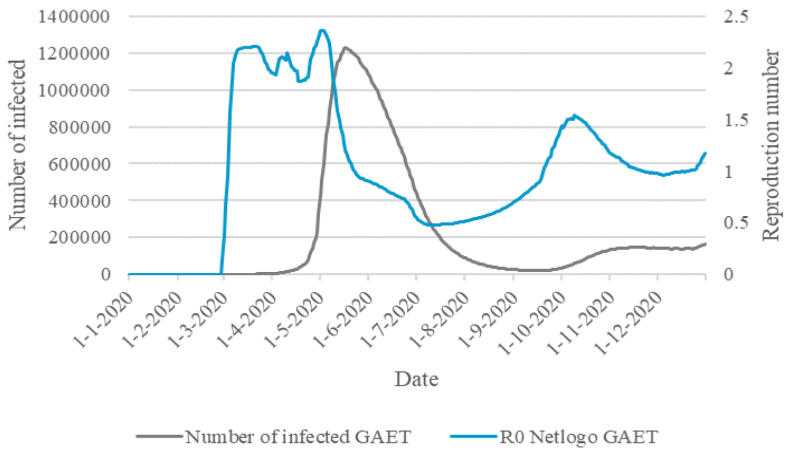

Figure 24. Number of infected individuals (left axis) and R_0 (right axis) caused by GAET simulated in Netlogo.

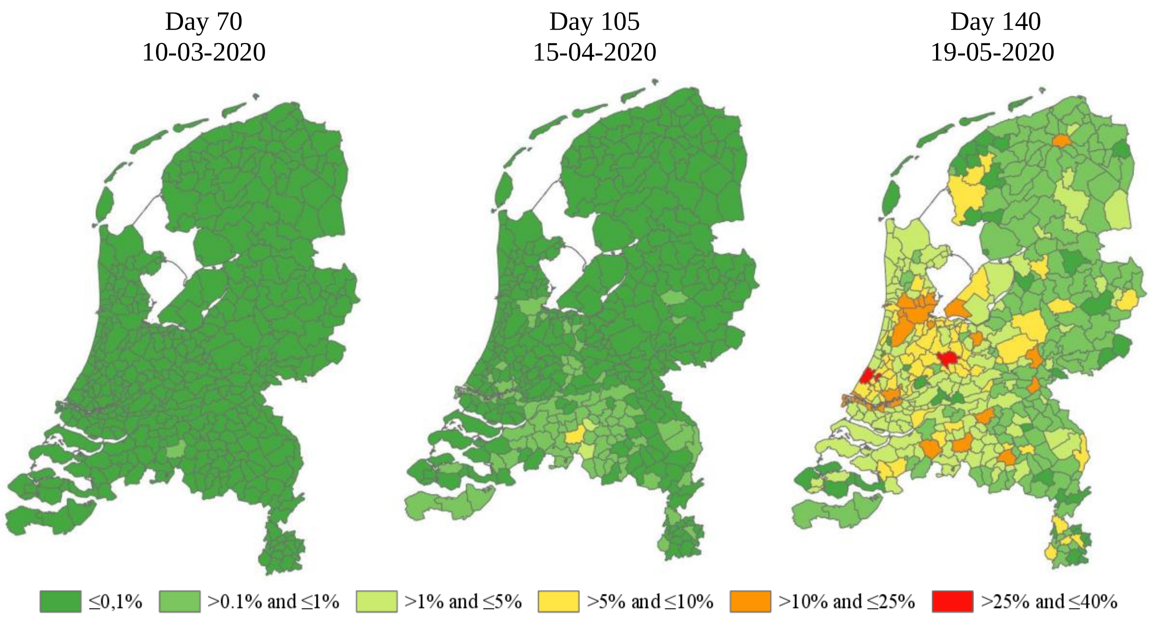

Figure 25. The percentage of the number of infected individuals in each municipality caused by GAET simulated in Netlogo.

Visit travelling

In this case, the only interaction between municipalities comes from VT, so this is without job commuting, school commuting and GAET. Figure 26 shows that the reproduction number is especially high at the start, which is a result of the rise of infected individuals in Tilburg itself. The small sharp peak in April 2020 is because a result of the spread of the virus due to VT. The figure shows relatively sharper peaks than the GAET figure (Figure 23), which is caused by the faster spread to other municipalities in comparison to GAET, resulting in many transmissions at once by VT.

In Figure 27 the first peak in reproduction number indicates a rapidly increasing number of infected, which is visible in the graph as a delay in peaks between the number of infected individuals and the reproduction number. The flat area at the start of the graph indicates the spread of the virus in Tilburg, the municipality where the virus is introduced. As the virus can only spread in Tilburg the reproduction number is steady. Afterwards, peaks are visible, caused by how the number of infected caused by travelling is calculated and how the reproduction number is calculated as explained in the previous section.

The number of infected individuals and the spread in the Netherlands in 2020 is visible in Figure 28. On day 70 the virus is only present in the municipality where the virus was introduced. On day 105 The virus spreads to neighbouring municipalities and larger municipalities in the case of VT, which is expected. This is a combination of relocation and expansion spread, spread to neighbouring and large non-neighbouring municipalities.

Compared to GAET, VT spreads very similarly (with only minor differences) to neighbouring and non-neighbouring municipalities, which is expected as the same travel flows are used as GAET. What stands out is that the first peak in the number of infected individuals is slightly smaller in the case of VT (Figure 27) than that of GAET (Figure 24). It cannot be concluded that there are differences between GAET and VT yet because the previously mentioned differences in the number of infected individuals and the maps are probably caused by running the model only once. The outcomes of the model with the same settings are not always similar, running it multiple times and taking the average would result in more stable outcomes. In section 5.2 the stability of the model is tested.

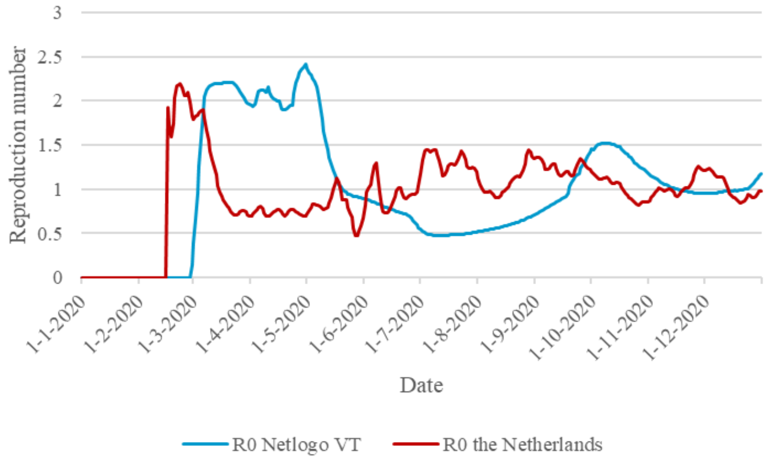

Figure 26. Reproduction number caused by VT simulated in Netlogo compared to the real reproduction number in 2020 (data source: RIVM[4], 2021).

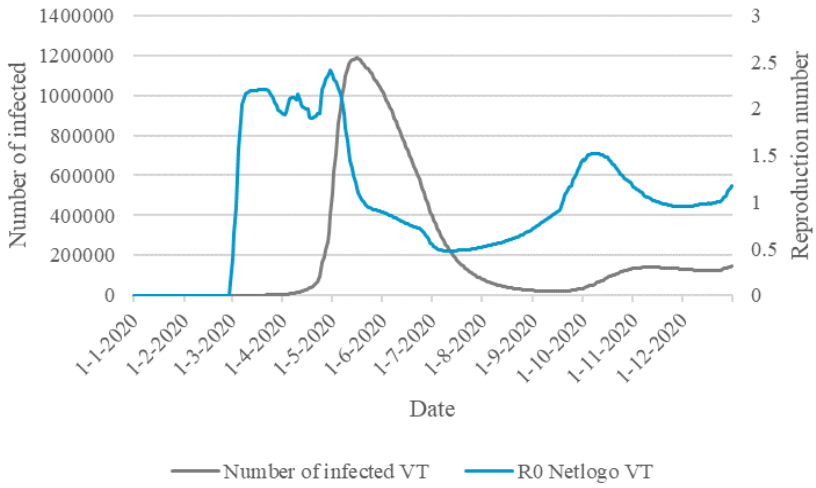

Figure 27. Number of infected individuals (left axis) and R_0 (right axis) VT simulated in Netlogo.

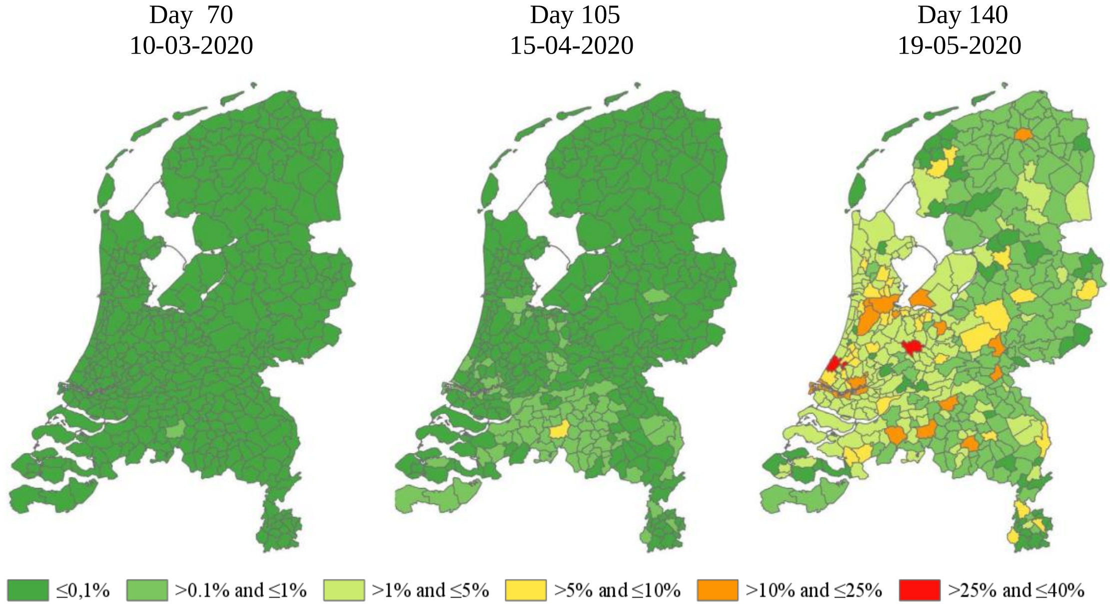

Figure 28. The percentage of the number of infected individuals in each municipality caused by VT simulated in Netlogo.

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Combinations of commuting and travelling

From the results of combining job commuting, school commuting, GAET and VT and running the model three figures are created (Figure 29, Figure 30 and Figure 31). The reproduction number shows higher peaks at the start of the simulation relatively to GAET and VT alone, although the number of infected is significantly higher, the pattern does match that of GAET and VT. Compared to the previous two runs for GAET and VT separately, this run results in a higher number of infected together with the virus spreading significantly faster, with at day 105 (15 April 2020) infected individuals in every municipality. As the virus covers a large part of the Netherlands already at day 105 it is suspected that it is caused by a combination of expansion spread as well as relocation spread. Although a large part of the Netherlands is covered, the virus is especially present in the Randstad and the municipalities with larger cities. Considering that large municipalities (in the Randstad) have a large share in the number of commuters and travellers links and that the virus does not disappear as easy in a large municipality, a large number of infected are expected. On day 140 (19 May 2020) the number of infected individuals covers the whole of the Netherlands what corresponds with Figure 31 where the peak lies in April and May with another rise in the number of infected at the end of October 2020. Since measures are not taken into account in these simulations, it is expected that the number of infected will be significantly lower and closer to reality when they are added when running the model.

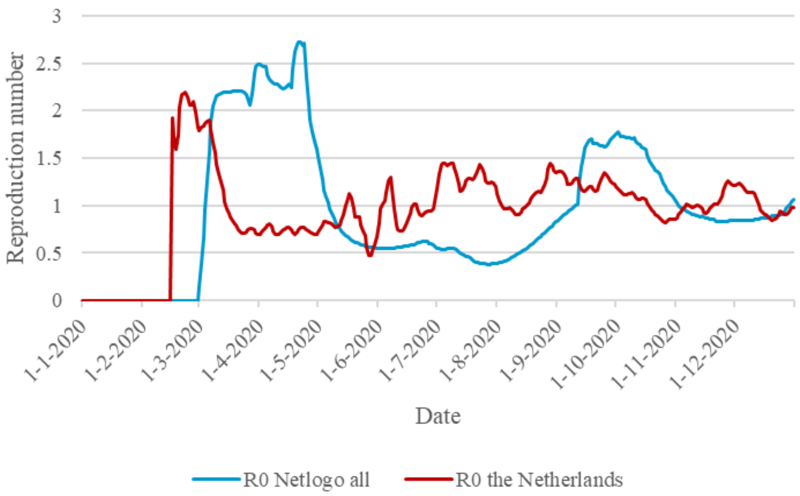

Figure 29. Reproduction number caused by job commuting, school commuting GAET and VT simulated in Netlogo compared to the real reproduction number in 2020 (data source: RIVM[4], 2021).

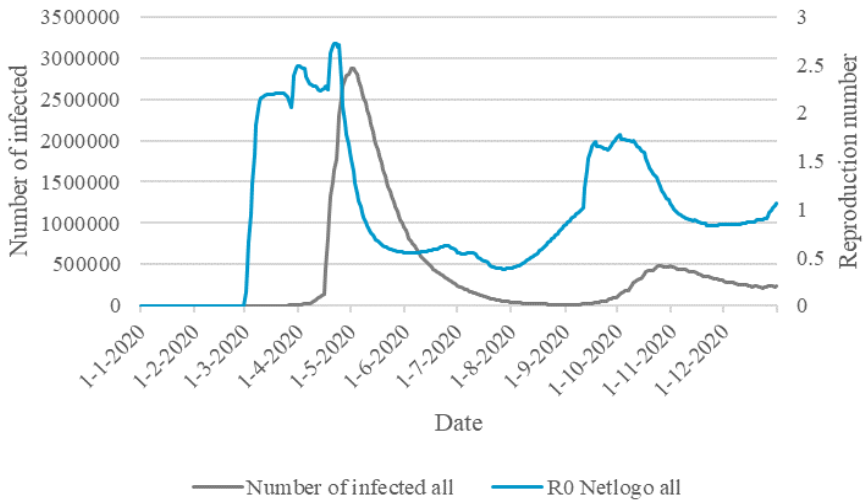

Figure 30. Number of infected individuals (left axis) and R_0 (right axis) job commuting, school commuting, GAET and VT simulated in Netlogo.

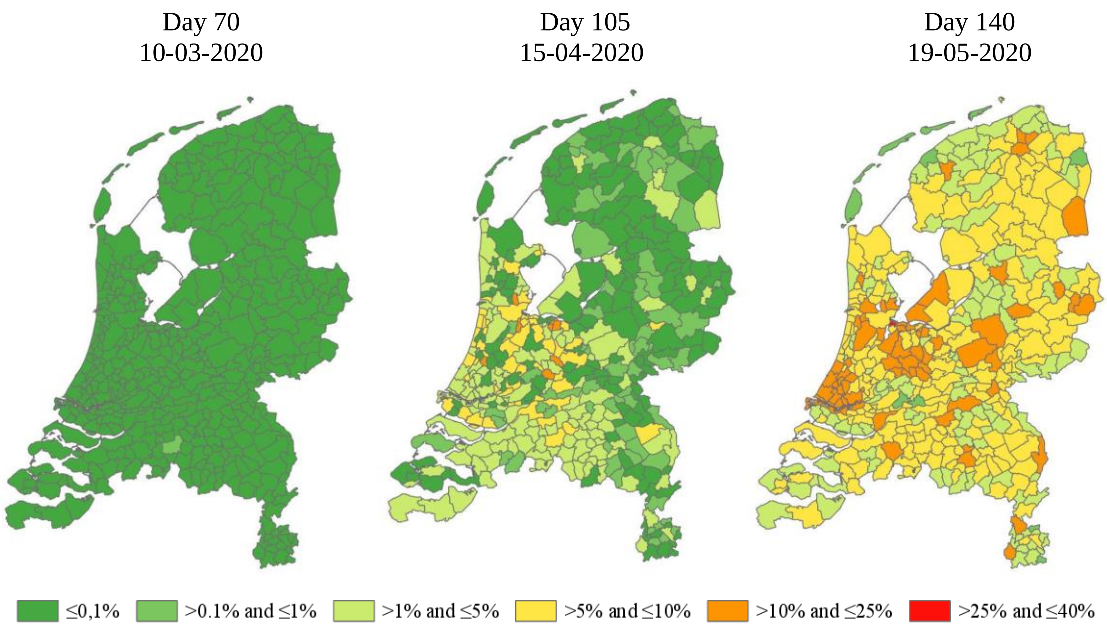

Figure 31. The percentage of the number of infected individuals in each municipality caused by a combination of job commuting, school commuting, GAET and VT simulated in Netlogo.

5.1.2 Lockdowns

To test if lockdowns interrupt the commuting and travelling in the model, the model is run twice: once simulating the pandemic including predefined lockdowns in 2020 in the Netherlands and once simulating the scenario without lockdowns. A difference in patterns is expected depending on the lockdown periods.

The first lockdown started on 23 March 2020 and ended on 11 May 2020 when the first measures were lifted (Ministerie van Volksgezondheid, Welzijn en Sport, 2020c). In most cases, a lockdown has a clear start date but does not necessarily have a clear end date. This is a result of (extra) measures being implemented at the start of a lockdown, while at the end of a lockdown often not all measures are lifted. An example of such a situation is the measure of working from home: this was advised from the start of the lockdown and the advice remained in place during the rest of 2020. However, on 1 July 2020 (week 27) a rise in the number of people checking in and checking out with the OV-card can be observed (Translink, 2021) (Figure 21) and therefore this date is used as the end of the lockdown for job commuting. The measures can also change in the first and second lockdown: it is for example allowed to have three individuals visiting someone at home during the first lockdown, while in the second lockdown this was reduced to one individual. The second lockdown started on 15 December 2020 and the first easing of restrictions of the lockdown happened on 28 April 2021. The lockdown in 2021 is not taken into account in this research.

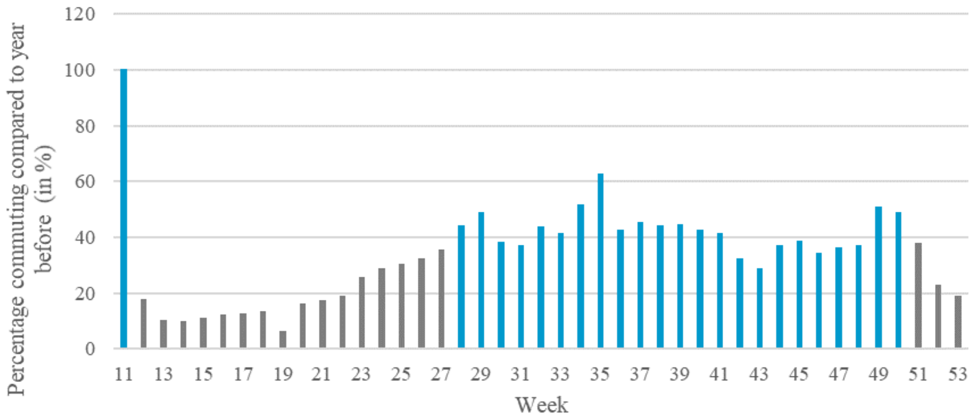

Figure 32. The difference in commuting in 2020 compared to the year before (grey = lockdown) (data source: Translink, 2021).

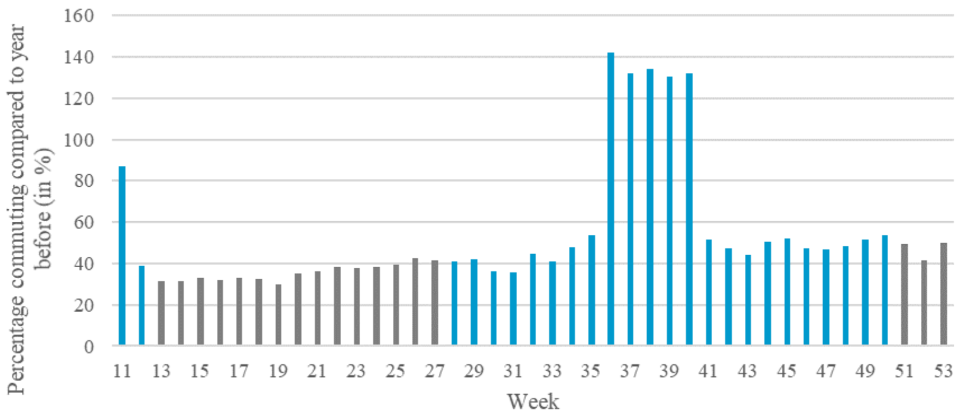

Figure 33. The difference in travelling in 2020 compared to the year before (grey = lockdown) (data source: Translink, 2021).

To simulate the lockdowns commuting was taken to be roughly 85% less during the first lockdown and taken to be roughly 70% less during the second lockdown (Figure 21 and 22) (Translink, 2021). Schools were taken as either open or closed during a lockdown and an in-between-scenario was not taken into account.

For GAET, the difference in travelling on the weekends in 2019 and 2020 is used. The travelling is reduced by roughly 80% in the first lockdown and by roughly 70% in the second lockdown (Appendix B-1 and B-2) (Translink, 2021). For VT the number of travels for each age group are derived from the survey answers (Table 6). The lockdowns, dates and reduction of commuting and travelling are shown in Table 9. The differences in the first and second lockdown hold only for the predefined lockdown runs and not for the scenarios.

	Start first lockdown	Reduction of commuting/ travelling	End first lockdown	Start second lockdown	Reduction of commuting/ travelling
Job commuting	March 16	85%	July 1	16 December	70%
School commuting	March 16	100%	June 1	16 December	100%
GAET	March 23	80%	July 1	13 October	70%
VT	March 23 (max. 3 individuals)	80%	July 1	13 October (max. 1 individuals)	70%

Table 9. Lockdowns in the Netherlands, 2020 (Ministerie van Volksgezondheid, Welzijn en Sport, 2020c).

By examining Figure 34 and Figure 35, it can be observed that the lockdowns do affect the reproduction number and number of infected. It can be seen that the first peak is much smaller compared to the model without a lockdown. Furthermore, the second peak in October/November is relatively larger with a lockdown compared to the situation without a lockdown. It is expected that this is caused by the setting of the duration of immunity to one year, which results in an individual not being able to get infected twice in one year. If fewer people are infected in the first peak, this may lead to more people being infected in the second peak because the number of susceptible is still larger. Therefore if the first peak is lower it means more people are not immune yet and can get infected in the second peak, which will be larger. In Figure 36 the spread of the virus with predefined lockdowns is presented. When comparing Figure 36 to Figure 31 it can be observed that the spread is similar, but that the number of infected individuals is significantly smaller. On day 140 the peak has already happened for the run without lockdowns (Figure 31) and therefore the virus is much more spread out already. While in Figure 36 the peak must still happen for the run with predefined lockdowns and therefore a few municipalities have (almost) no infected individuals. In other words, the differences in the timing of the first peak result in different outcomes in both figures. Hence, the run with predefined lockdowns, which has a much lower number of infected individuals, looks like a delayed version of the run without lockdowns.

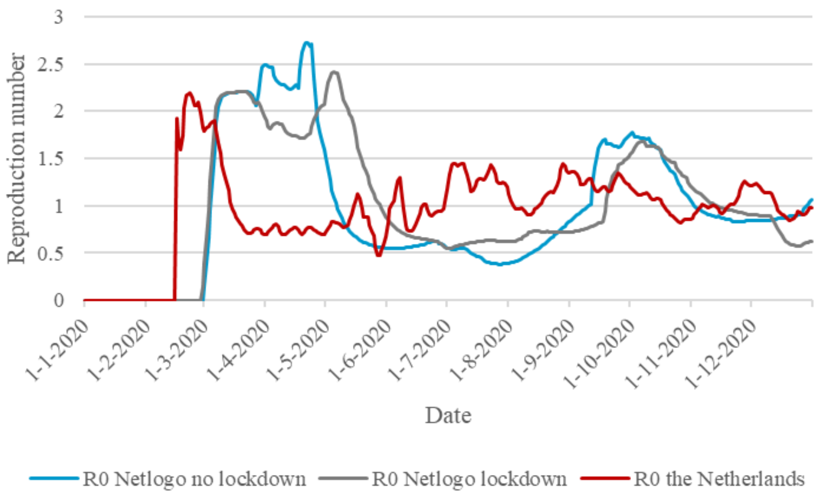

Figure 34. Reproduction number caused by job commuting, school commuting GAET and VT simulated in Netlogo with and without lockdowns compared to the real reproduction number in 2020 (data source: RIVM[4], 2021).

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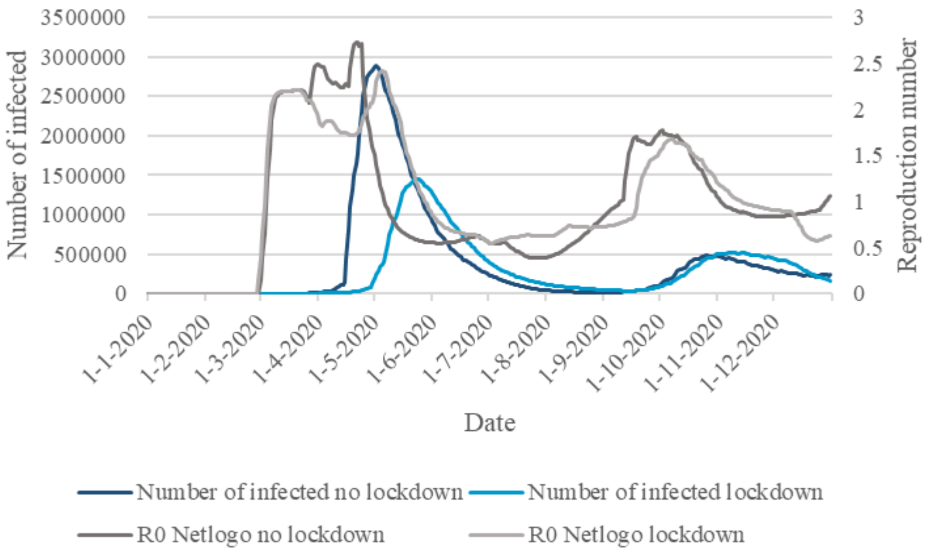

Figure 35. The number of infected individuals (left axis, blue) and R_0 (right axis, grey), job commuting, school commuting, GAET and VT simulated in Netlogo with and without lockdown.

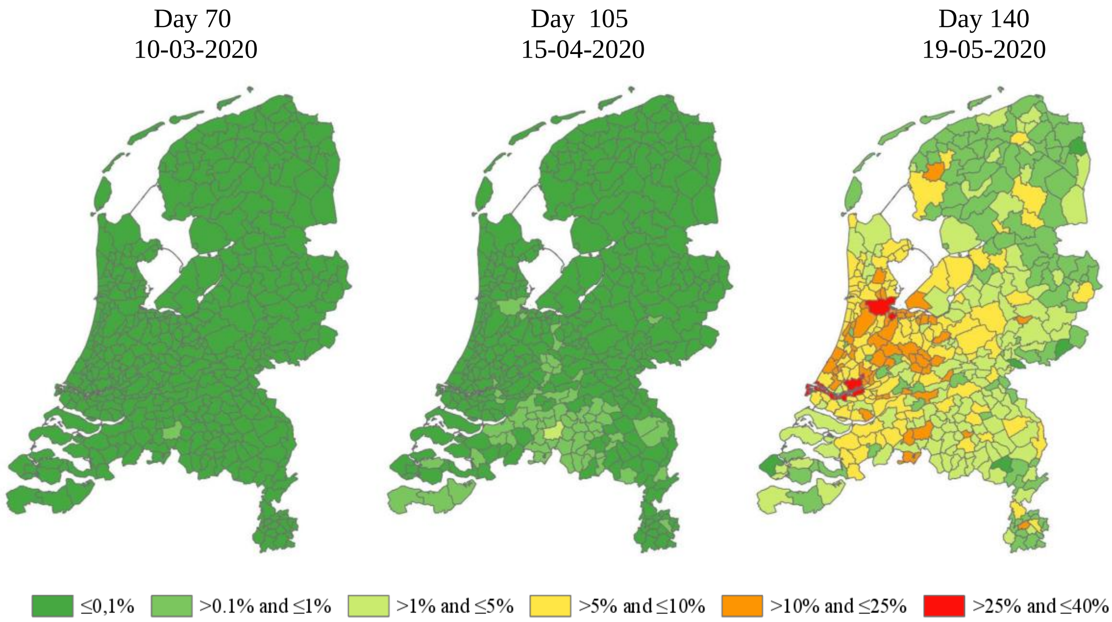

Figure 36. The percentage of the number of infected individuals in each municipality caused by a combination of job commuting, school commuting, GAET and VT simulated in Netlogo including predefined lockdowns.

The number of hospitalizations resulting from the number of infected can be seen in Figure 37. The shape of the graph is similar to a ratio of 0.0255. The number of infected individuals is used to calculate the number of hospitalizations for all age groups and therefore these graphs look similar. The ratio for each age group is visible in Table 7. It can be observed that the first peak is relatively much smaller compared to the model without a lockdown. Furthermore, the second peak in October/November is relatively larger with a lockdown compared to the situation without a lockdown. In the case of the hospitalizations, the graph that includes a lockdown is more favourable, as the number of hospitalizations is better divided and it will therefore put less of a burden on the health care system (Santos, 2020). The number of hospitalizations is still relatively large, but by calibrating the infectiousness of the disease more realistic numbers are expected.

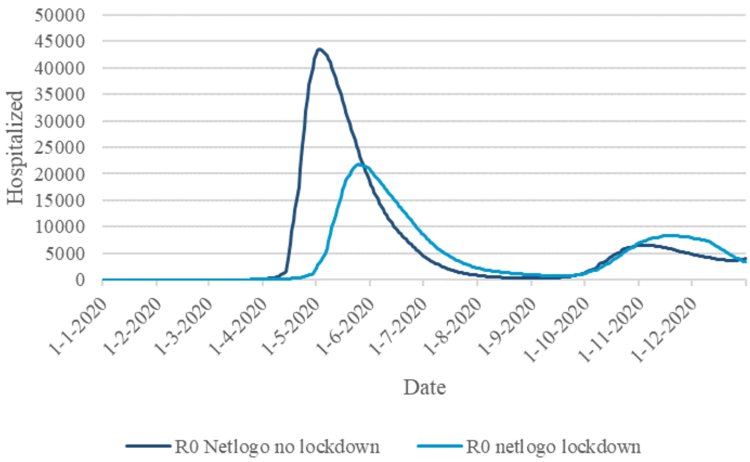

Figure 37. The number of hospitalized job commuting, school commuting, GAET and VT simulated in Netlogo.

5.1.3 Change of contact matrix

The change in the contact matrix is applied by multiplying the contact matrix with a ratio for all municipalities. This is a simplified method, which makes it possible to reuse the existing contact matrix and avoid that multiple new contact matrices need to be created. In the initial model, there was just one contact matrix. In the new model, the contact matrix changes when restrictions are implemented per age group. It is chosen to change it per age group because risk perception and coping appraisal differ strongly within different age groups. To test if this works, different contact matrices ratios are implemented during the run with the model without a lockdown. Three runs are performed: in the first run the ages 0 to 25 years have a ratio of 0.2 between March and July 2020, in the second run the ages 25 to 65 years have a ratio of 0.2 between March and July 2020 and in the third run, the ages 65+ years have a ratio of 0.2 between March and July 2020. The age group 0 to 25 years consist of children, young teenagers, old teenagers and young adults. In the calibration and age group scenario, these will be examined separately as it is expected that they can behave differently. For the verification, it is not necessary to dive deeper into this yet. A ratio of 0.2 for a certain age group means that the number of contacts an individual in an age group has will only be 1/5 of their normal contact and this should lead to fewer infections in this age group. Therefore, if an individual normally meets five other individuals a day this will be reduced to only one individual. Both the runs are compared to a run without any restrictions. The runs are performed in Tilburg and therefore there is no commuting or travelling.
In Figure 38 and Figure 41 similar graphs for the age group 0 to 25 years and 65+ years with and without restrictions is presented. The graphs show that restrictions do have a significant influence on the number of infected in this age group. The graph also shows a delay in the rise of infected individuals compared to the line representing no contact restrictions. Although the first peak is smaller the second peak is larger, probably because there are still more susceptible individuals. So it leads to fewer infections during the period in which the ratio was implemented, and more infections during the next wave without the ratio.
Figure 39 is different from both the other figures because the first peak is slightly smaller and the second peak slightly larger than the peaks of the graph without restrictions. The restrictions cause a delay in the rise of hospitalized individuals and do not seem to result in fewer infected individuals in the age group 25 to 65 years old. This is mainly caused by the job commuting in which these age groups take part. In Figure 40 this is shown: The peak of the run with the model with restrictions and without job commuting causes a decline in the

number of hospitalized individuals, although it is not as much as for the other age groups. In section Calibration 5.4 the calibration will be further discussed.
From the previous sections, it can be concluded that the models' behaviour on all of the experiments is as expected. It can be concluded that the core functionalities of the model are working.

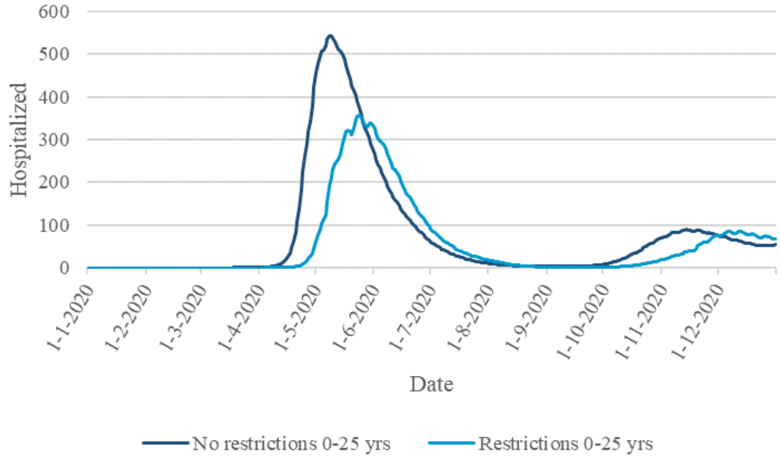

Figure 38. The number of hospitalized job commuting, school commuting, GAET and VT for the age group 0-25 years simulated in Netlogo.

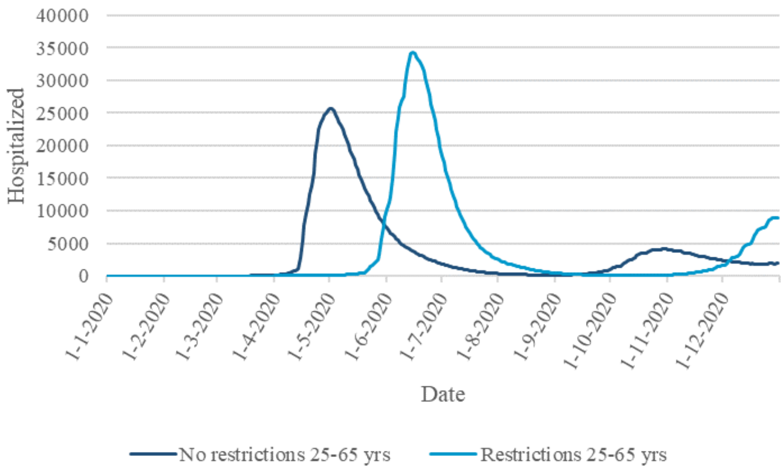

Figure 39. The number of hospitalized job commuting, school commuting, GAET and VT for the age group 25-65 years simulated in Netlogo.

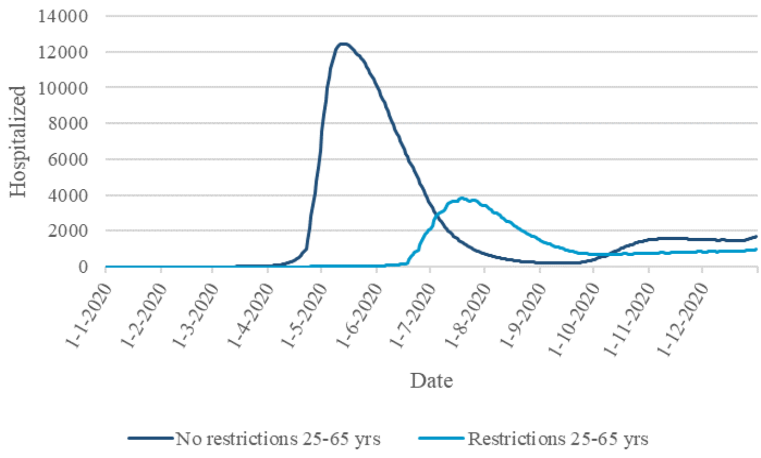

Figure 40. The number of hospitalized school commuting, GAET and VT for the age group 25-65 years simulated in Netlogo (excluding job commuting).

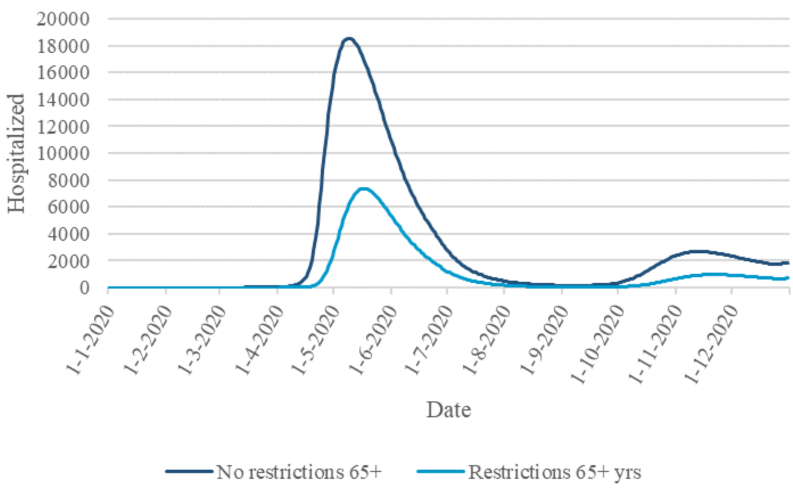

Figure 41. The number of hospitalized job commuting, school commuting, GAET and VT for the age group 65+ years simulated in Netlogo.

5.2 STABILITY MODEL

Before the sensitivity analysis can be performed the stability of the model must be checked by running the model several times and calculating the coefficient of variation. The coefficient of variation (c_v), a statistical measure, is chosen because it makes it possible to compare different datasets and it provides a "dimensionless and normalized measure of variance" (Lorscheid et al., 2012, p. 33). The ratio of the standard deviation to the mean represents the coefficient of variation:

(6) $c_v = s/\mu$

c_v = *the coefficient of variation*
s = *standard deviation*
μ = *arithmetic mean of a set of values*

(Hendricks & Robey, 1936)

The model is run an increasing number of times (in steps of ten runs) and for every number of runs, the mean and coefficient variance is calculated from the number of infected individuals. The same settings are used for each run and in this case, the job commuting, school commuting, GAET, VT and the lockdown are turned on. The higher the number of runs the more stable the variability of the variation of the coefficient is (Lorscheid et al., 2012). Therefore, the stability of c_v can specify the number of runs (N) required to run the model. In Figure 42 is the graph showing the coefficient of variation of the model for 150 runs.
The coefficient of variation is often shown in percentage. According to Brown (1998) is a coefficient of variation above 30% indicates problems in the data or the experiment. In Figure 42 it can be seen that the coefficient of variation is fluctuating a lot between 1 to 50 runs, but becomes more stable after 25 runs. A coefficient of variation of +/- 7.5% is very good and therefore fine for this research.
The more runs the higher certainty there is, but this comes at a cost. In other words, there is a trade-off between costs and stability (Lorscheid et al., 2012). In this research, the cost is the time the model needs to run and the computer power necessary. To run the model 100 times with the settings mentioned above takes ~5 hours. As there are time constraints to this thesis it is decided to do 25 runs during the research, which takes ~1.2 hours.

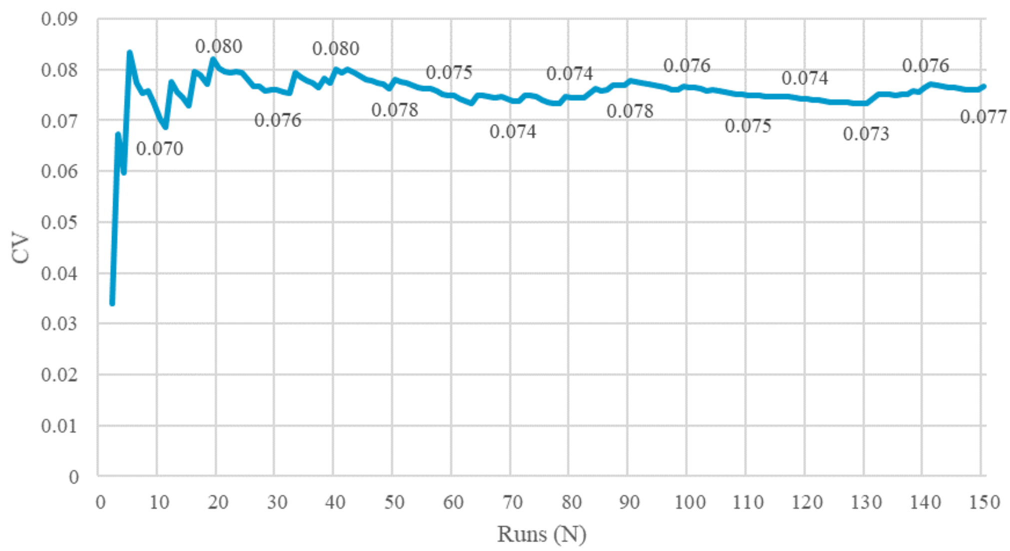

Figure 42. The coefficient of variation of the Netlogo model.

5.3 SENSITIVITY ANALYSIS

In the sensitivity analysis, it is determined which variables need to be calibrated. The exposed, infected and recovered period were already covered by Tjalma (2016), therefore these are not covered in this thesis. This sensitivity analysis focuses on the transmission rate as it is expected that the partly unknown values of the transmission rate have a large impact on the behaviour of the model.

5.3.1 Transmission rate

It is expected that the transmission rate, derived from the infection rate and contact rate, has a high impact on the number of infected. The contact rates have been acquired by Tjalma (2016) via the RIVM. The transmission rate is identified by Sun et al. (2020) to be around 2.2 for COVID-19. Furthermore, the transmission rate changes during the year depending on the season and is lower in the summer and higher in the winter. The exact values of the transmission rates during the year are unknown.
To test the sensitivity of the transmission rate the model is run 25 times for commuting, GAET, VT and a combination of commuting and travelling each. To test the sensitivity of the transmission rate the model is run with a transmission rate based on the influenza of 0.2 (Del Valle et al., 2007), a transmission rate of 0.8 and a transmission rate of 2.0. In the graphs, the exposed individuals are taken into account, but not shown. It is expected that at a low transmission rate of 0.2, COVID-19 does not spread at all within and outside of the municipality where the virus is introduced in case of commuting and travelling.

Job and school commuting transmission

In Figure 43 the fractions of susceptible, infected and recovered are shown for three different transmission rates. When the model is run with the smallest rate (0.2) no infections are generated at all, therefore it can be concluded that this transmission rate is too low to create a COVID-19 outbreak. A transmission rate of 0.8 causes a rise in infected individuals in May 2020. With a transmission rate of 2.0, a similar pattern can be seen in the graph, however, the number of infected is higher and the large outbreak starts a month earlier in April 2020. In the

calibration, this thesis will dive deeper into selecting the transmission rates for the model and this section mainly focuses on the sensitivity of the model.
A similar sensitivity analysis is performed by Tjalma (2016, p. 45), but the results are different. This is mainly because the infected period for COVID-19 (6 - 9 days) is shorter than that of pertussis (21 days). Therefore a transmission rate of 0.2 does cause a rise in infected individuals for Pertussis and therefore the transmission rate is even more sensitive than in the COVID-19 case, which does not get a rise in infected with a transmission rate of 0.2. In the Pertussis model, the number of susceptible and recovered do cross each other and the number of recovered reaches a fraction of 0.8 in case of a transmission rate of 0.2, and a fraction of 0.97 in case of a transmission rate of 2.0. These Pertussis fractions are rather high and are not reached in the COVID-19 graphs below and therefore it can be concluded that the transmission rate is less sensitive in the updated model.

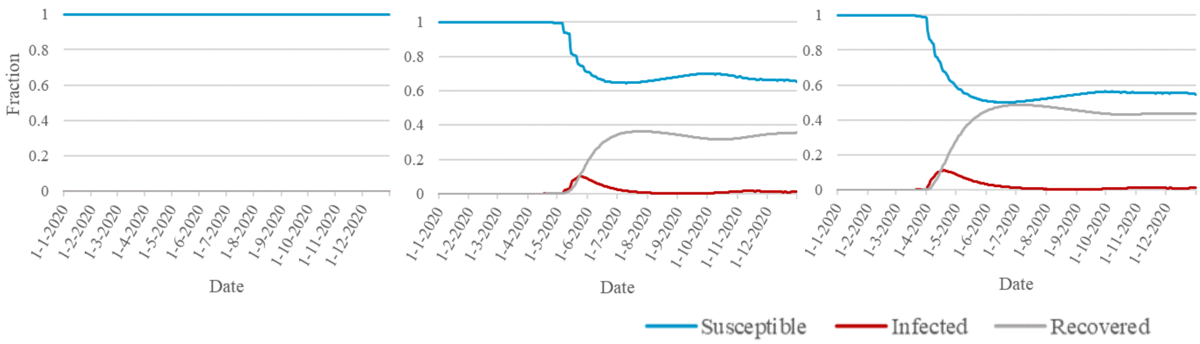

Figure 43. Fraction susceptible, infected and recovered in the Netherlands together with job commuting, school commuting simulated in Netlogo (transmission rate 0.2, 0.8, 2.0).

Gatherings and events and visit travelling transmission
In Figure 44 and Figure 45 the fractions of GAET and VT are presented. Also in this case there is no outbreak when the transmission rate is 0.2. Similar to Figure 43 a transmission rate of 2.0 causes a large outbreak a month earlier than with a transmission rate of 0.8. Figure 44 and Figure 45 are similar, which is expected as they share the same code and they both make use of the same job commuting link file.

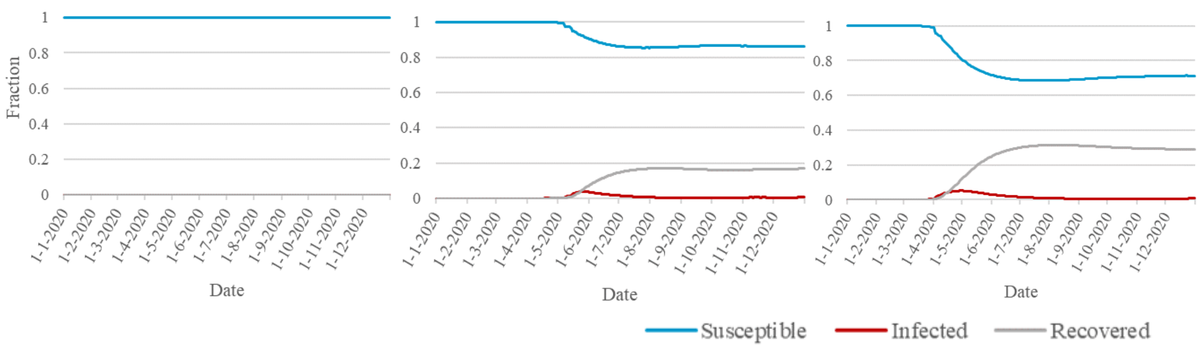

Figure 44. Fraction susceptible, infected and recovered in the Netherlands together with GAET simulated in Netlogo (transmission rate 0.2, 0.8, 2.0).

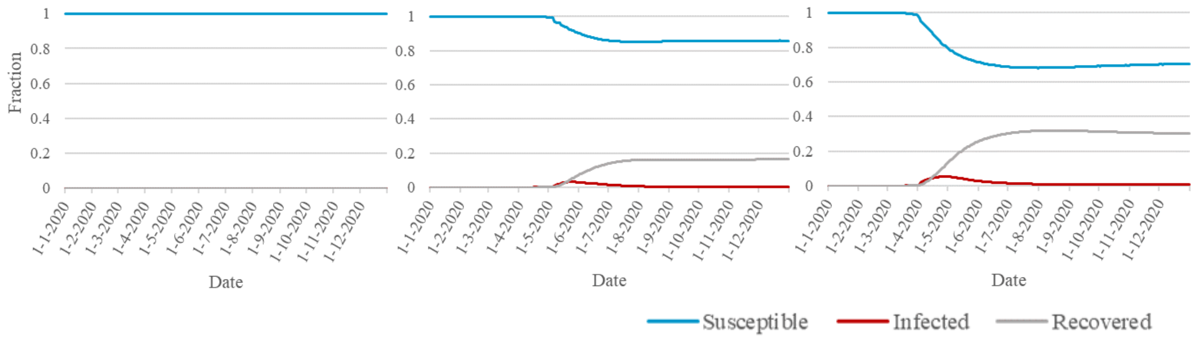

Figure 45. Fraction susceptible, infected and recovered in the Netherlands together with VT simulated in Netlogo (transmission rate 0.2, 0.8, 2.0).

Commuting and Travelling

Again, when running the model with commuting as well as travelling at the smallest rate, no infections are generated at all. In this case, the transmission rate is too low for an outbreak to occur (Figure 46). When taking a closer look at the middle and right graph it can be seen that the number of infected is rising and declining, while the number of recovered is almost only rising or steady. The duration of the recovered period is one year and therefore it is expected that the number of recovered will (almost) not decline the first year. A difference between the graphs is the small second peak visible at the end of the graph with the transmission rate of 0.8. With a lower transmission rate, it is thus possible to create a second peak.

The peaks in the number of infected and recovered individuals are larger when the model with commuting as well as travelling is run than when they are run separately. This is as expected as the virus spreads faster and therefore infects more individuals in a shorter amount of time.

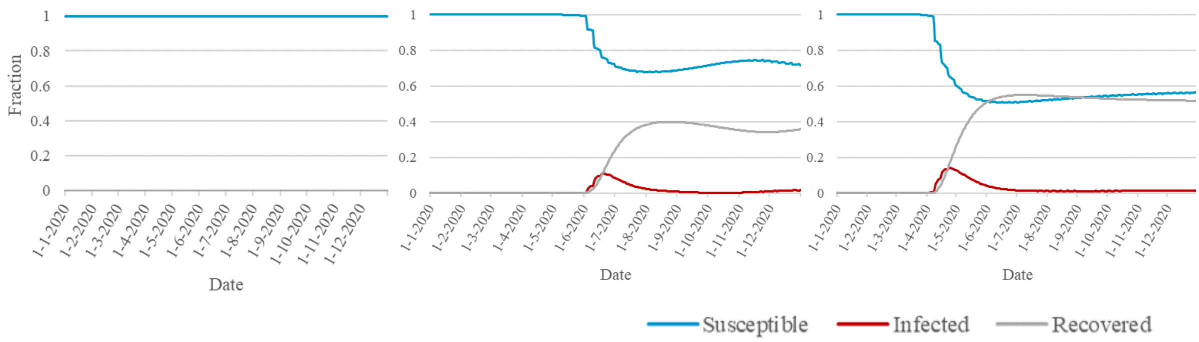

Figure 46. Fraction susceptible, infected and recovered in the Netherlands together with commuting and travelling simulated in Netlogo (transmission rate 0.2, 0.8, 2.0).

From the previous graphs, it can be concluded that the transmission rate does have a large impact on the behaviour of the model. The transmission rate mostly impacts the number of infected as well as the time the first large COVID-19 outbreak happens.

5.4 CALIBRATION

From the sensitivity analysis, it is known that the transmission rate has a high impact on the model’s outcomes, compared to other parameters. In this section, the transmission rate is used to calibrate the model. It is chosen to calibrate this parameter together with the infectious period and day of the outbreak because of the time restrictions for this project and due to the complexity of the model: the parameters can influence each other, which makes calibration of

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multiple parameters too complex. Since there is data available, which was tracked and updated by the RIVM for 2020, it is possible to adjust the parameters in such a way that the results of the model and the actual numbers of patients of the COVID-19 pandemic in 2020 are comparable. The value of the transmission rate can be based on the reproduction number and the number of infected and hospitalized individuals. The patterns in the RIVM graphs are discussed in section 5.4.1. The goal is to use the model to create similar graphs with matching patterns, without over calibrating. In section 5.4.2 the seasonal transmission rate is discussed. In the next section (5.4.3) the number of infected and hospitalized individuals per age group is examined and calibrated. The last two sections consist of the calibration of the infectious period (5.4.4) and the day of the outbreak (5.4.5).

5.4.1 Patterns graphs

This part of the calibration starts by indicating what kind of patterns are necessary to imitate the COVID-19 outbreak in the model. In Figure 47 the reproduction number is visible, the chosen transmission rates must result in the same reproduction number pattern in the model.

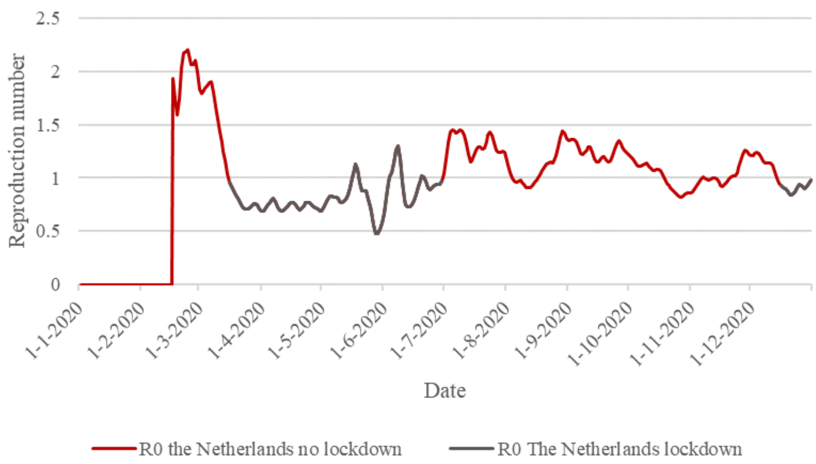

Figure 47. The reproduction number in the Netherlands in 2020 (Data source: RIVM[4], 2021).

In Figure 48 the number of positive tests and the number of infectious individuals as estimated by the RIVM is shown. This comparison shows that the second peak of infectious individuals should be almost as large as the first peak, therefore it can be concluded that the graph about the number of infected resulting from running the model should result in a similar pattern. Additionally, it can be concluded that the number of positive tests is significantly smaller than the number of actual infectious individuals because not every individual takes a test if experiencing symptoms, furthermore a part of the infected individuals are asymptomatic and are not aware of being infected. Furthermore, the graph proves that there should be three peaks in 2020: the first one around the end of March, the second one in October and the third one soon after in December. In the summer months, there should be almost no infected, but the R_0 should not be zero. It should be noted that the number of infectious individuals can be lower or higher than what is indicated in the graph as it is an estimation, and the exact number of days that an individual is infectious is not known. It should also be noted that the number of infected individuals resulting from running the Netlogo model will be higher than indicated by the RIVM[3] (2021).

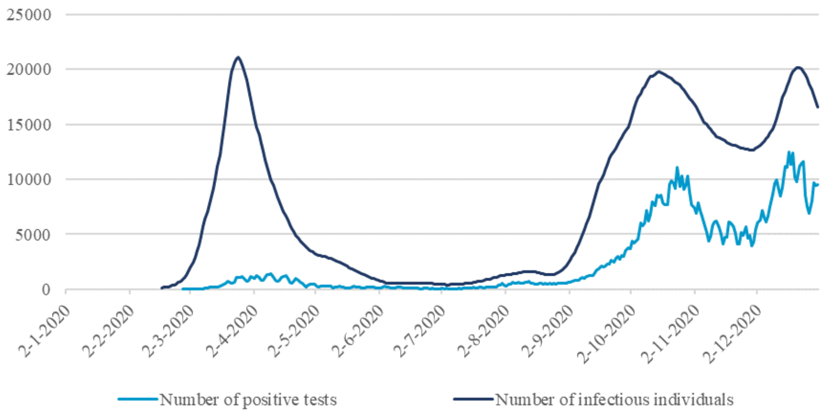

Figure 48. The number of positive tests and the number of new infectious individuals per day in 2020 according to the RIVM (Data source: RIVM[3 & 7], 2021).

In Figure 49, COVID-19 hospital bed occupation in 2020 is shown. This figure shows the same pattern as the number of infectious individuals in Figure 48. This graph also proves that there should be three peaks in 2020: the first one around the end of March, the second one in October and the third one soon after in December. The differences between Figure 48 and Figure 49 is that the second and third peak in October and December are not as high as the first peak. This is because, in the first peak, there was not a lot known about the treatment of COVID-19 patients, which caused patients to be in the hospital for a longer period of time than in the second half of 2020.

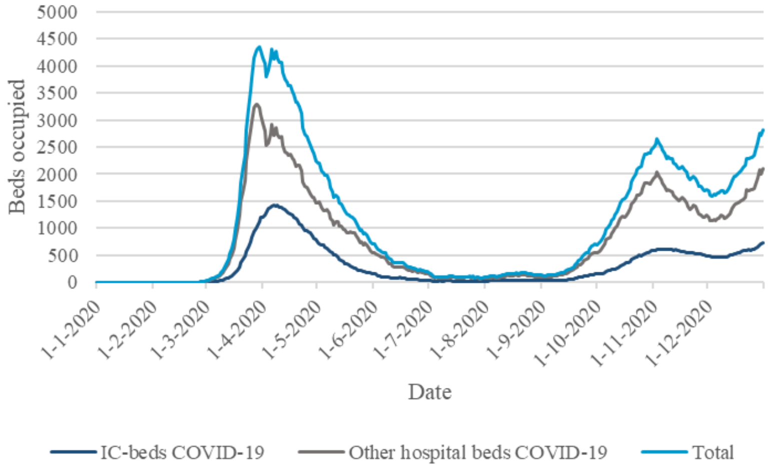

Figure 49. COVID-19 hospital bed occupation in 2020 according to the LCPS (Data source: LCPS, 2021).

5.4.2 Calibration seasonal transmission rate

Now that it is known what kind of patterns should result from running the model, it is possible to take a closer look at the transmission rates and assess which ones are appropriate to use. Besides changing seasonally, it is also possible for the transmission rate to be lower during a lockdown, this will be discussed later and is not added to the next graphs. Figure 50 shows what happens when the model runs one transmission rate through 2020. A transmission rate of 0.2 and 0.4 (Figure 50.1) is too low for the outbreak to start and dies out quickly. Although this transmission rate is not useful to increase the number of infected at the start it could be interesting to use the transmission rate of 0.2 and 0.4 in summer as it at least causes the number of infected individuals to decrease slower than a transmission rate of 0.1 or 0.05 and the virus does not cease to exist completely. The transmission rates of 0.6 to 2.0 (Figure 50.2 to Figure 50.6) do have a similar pattern: they all start with a peak and all have a

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second peak. Besides the similarities there are some significant differences: The first peak starts later with a lower transmission rate and the second peak is lower (and almost not visible) if the transmission rate is higher. In Figure 50.2 the second peak is not visible as it takes place in January 2021, outside the graph.

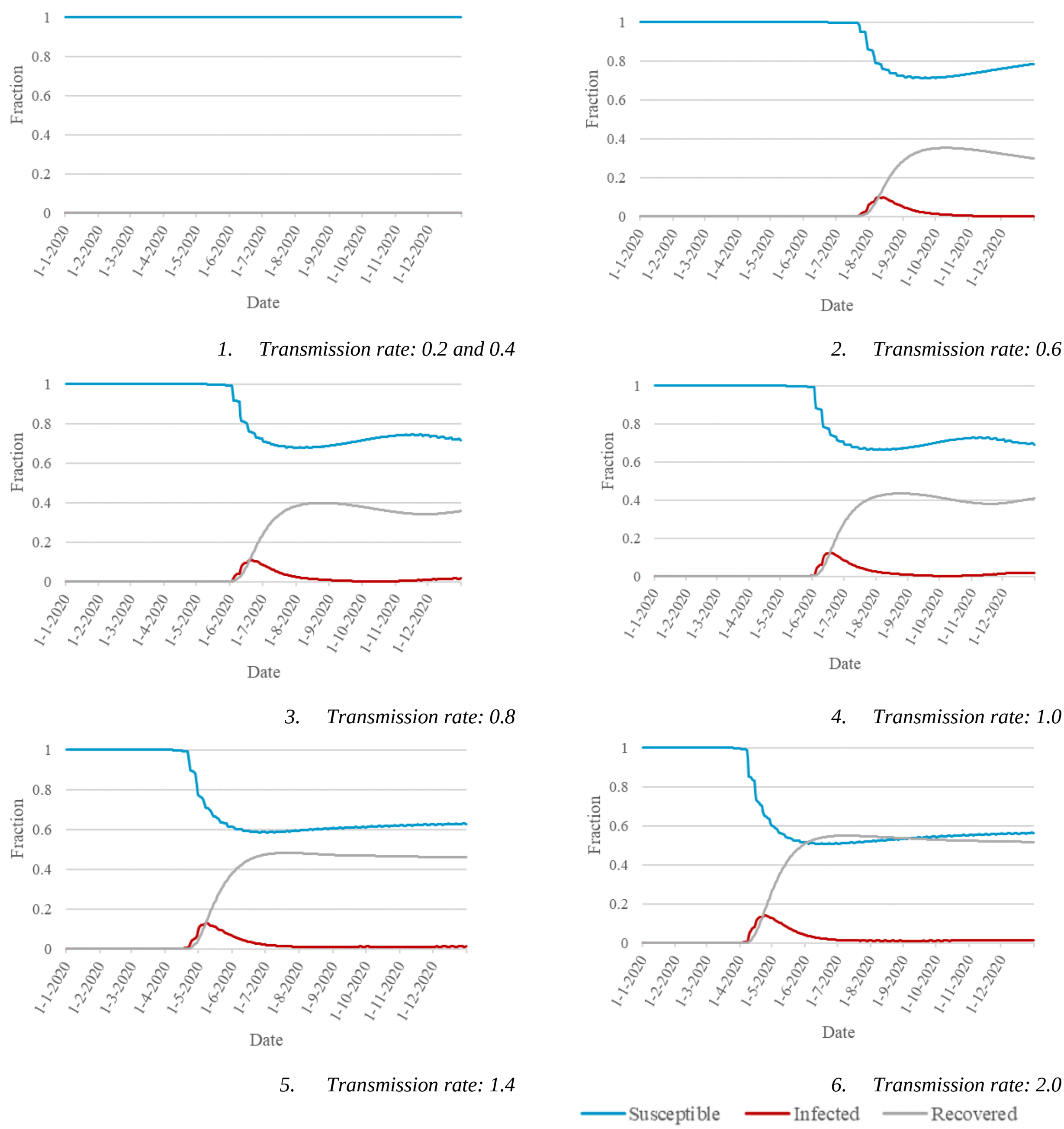

Figure 50. The fraction of susceptible, infected and recovered individuals caused by a change in the transmission rates simulated in Netlogo (including commuting and travelling).

A combination of transmission rates must be made to imitate the COVID-19 pandemic in the Netherlands in 2020. It should be taken into account that the transmission rate that is chosen does not include the lockdown measures and as a result, the reproduction number, the number of infected and the number of hospitalized individuals will be higher or lower than reality. Moreover, a period with a lower transmission rate does not necessarily lead to a period with a lower reproduction number, because the reproduction number is also influenced by the transmission rates during the periods beforehand and the number of infected and recovered

when this period starts. The same applies to a higher transmission rate: if there is a high fraction of recovered individuals the number of infected can go down even when the transmission rate is high. In other words, the transmission rate influences the reproduction number, but they do not increase or decrease each other equally.
Since the first peak starts in March (Figure 48) the transmission rate of 2.0 is chosen to start within the winter. A lower transmission rate, like a transmission rate of 1.4, in combination with other seasonal transmission rates, proved to result in a too low number of infected and hospitalized and results in a long-lasting first peak, which does not resemble the RIVM data. For the transmission rate in the spring and autumn, a transmission rate of 1.4 is chosen, because this transmission rate causes a slight decrease in infected individuals. Together with a transmission rate of 1.0 in the summer, the summer months have a low number of infected individuals.

The numbers obtained from the RIVM are of course influenced by the lockdown and additional restrictions. Therefore, the next step is to add the lockdowns as created in the verification. The transmission rate for commuting and travelling change seasonally, but are fixed for each season and the fixed seasonal rates cannot be altered during a run of the model. As a result, the (seasonal) transmission rates for commuting and travelling are fixed over the course of the run. Although the rates themselves cannot be changed, how the rates are implemented can be changed: by using ratios that can be varied throughout a run and multiplying those with the number of infected commuters and travellers, a net variation can be accomplished as this ‘adapted’ number of infected commuters and travellers is then taken into account with the transmission calculations. Hence, the number of commuters and travellers could still be varied between lockdown periods.
However, as stated earlier the general transmission rate of the model does change during the lockdown; accordingly, the transmission rate should be lowered for each season. When running the model, it became clear that lowering the transmission by one or two steps yields the best results. The winter transmission rate goes from 2.0 to 1.4, the autumn and spring transmission rate from 1.4 to 0.8 and the summer transmission rate from 1.0 to 0.6. This results in the fraction graphs of Figure 51, which show on the left the fraction graph without lockdown and on the right the fraction graph with the lockdown. In the left graph, the first peak at the end of March and the second peak in October can be seen. It would be preferable to have this peak already start in September. By implementing the lockdown measures the right graph can be created, which better represents the COVID-19 pandemic in 2020. In this graph, the second peak starts in October.

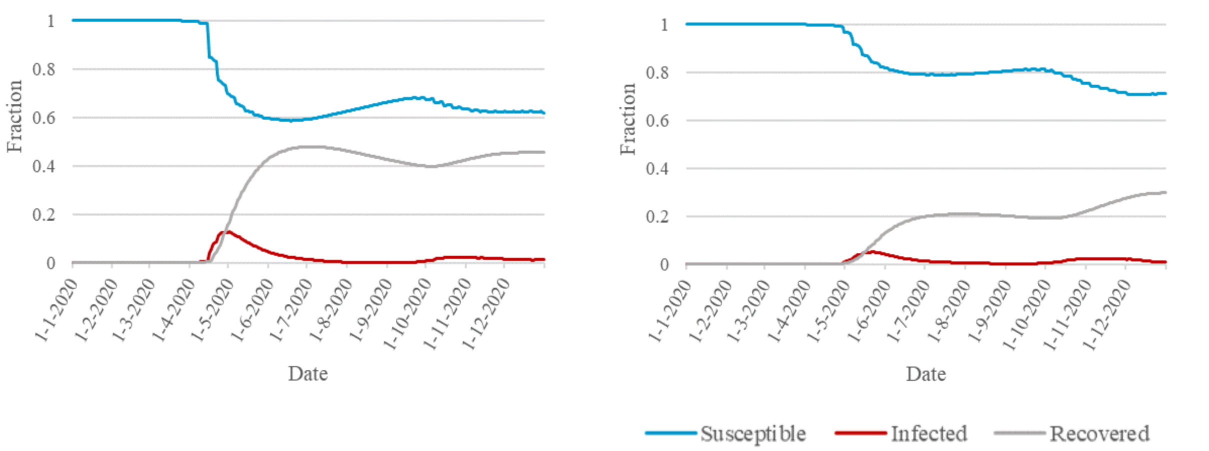

Figure 51. The fraction of susceptible, infected and recovered individuals caused by transmission rates of 2.0, 8.0 and 4.0 simulated in Netlogo (including commuting and travelling). Left is without lockdowns; right is with

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lockdowns.

To better understand the differences between the transmission rates implemented with and without a lockdown, Figure 52 and Figure 53 need to be studied. These figures show the reproduction number produced by the Netlogo model compared to the reproduction number as recorded by the RIVM. With a transmission rate of 2.0 the reproduction number is rather high (+/- 2.7), which is higher than the 2.0 it should be at the start of the COVID-19 outbreak and therefore too high. Even though this reproduction number is rather high in Figure 53, the rest of the graph seems to slightly align with the reproduction number recorded by the RIVM. Multiple runs have been executed and this is the closest the R_0, as produced by the Netlogo model, gets to the RIVM reproduction number.

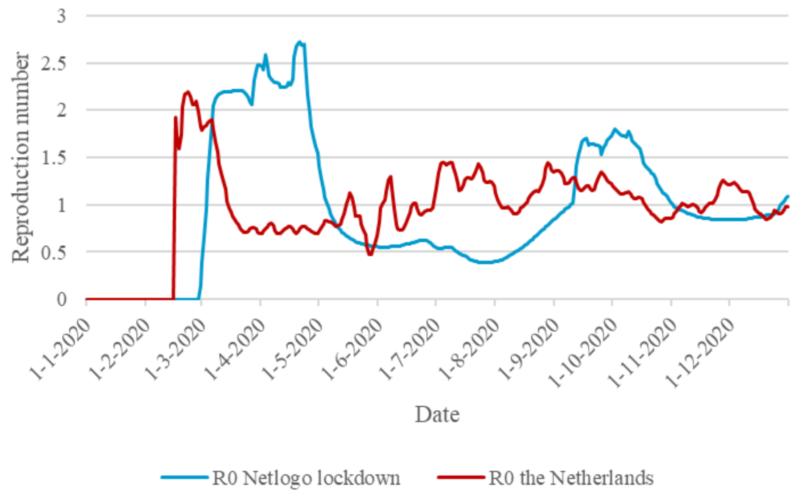

Figure 52. Reproduction number simulated in Netlogo without lockdowns and the reproduction number as recorded by the RIVM (data source: RIVM[4], 2021).

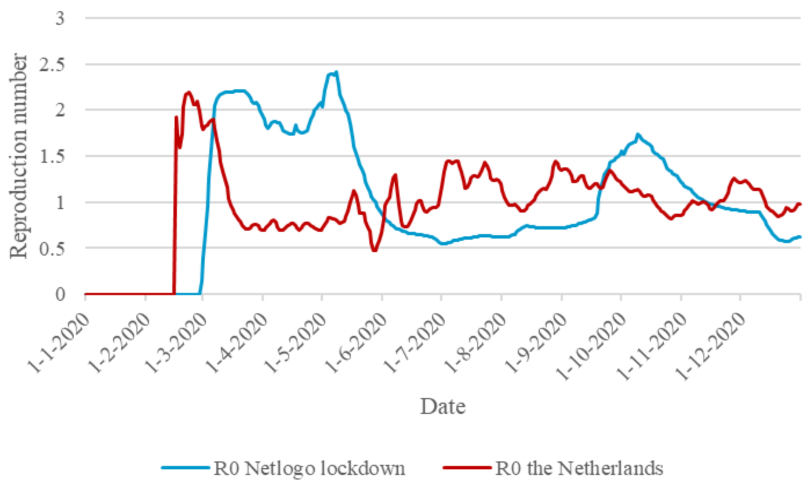

Figure 53. Reproduction number simulated in Netlogo with lockdowns and the reproduction number as recorded by the RIVM (data source: RIVM[4], 2021).

In Figure 54 it can be observed that the number of hospitalized, as recorded by the RIVM (LCPS), differs significantly from the number of hospitalized resulting from the Netlogo model. As predicted the number is different and it is expected that this will not influence the research as the research focuses on patterns. In the graph, it can also be seen that the first peak starts a month earlier and the second peak is split in two for the case of the number of hospitalized recorded by the RIVM. Although there are differences, the peaks are near each other and the number of hospitalized individuals in the summer is low. In the next section, the number of hospitalized and infected individuals are studied and possibly calibrated concerning their age groups.

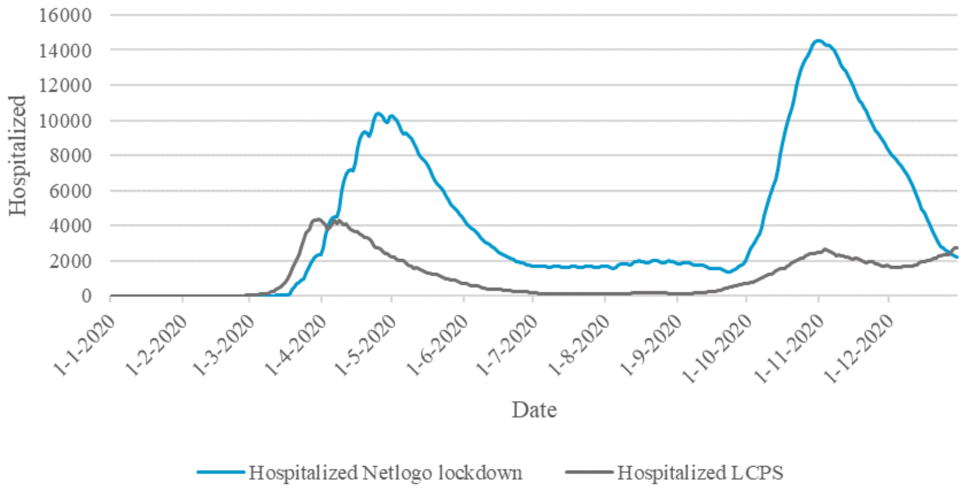

Figure 54. The number of hospitalized individuals simulated in Netlogo and as recorded by the LCPS (data source: LCPS, 2021).

5.4.3 Calibration age groups

In the next part of the calibration, this research will dive deeper into the age groups and specifically the distribution of the age groups. To identify what is expected from the model the RIVM data needs to be studied. In Figure 55 the positive test as documented by the GGD per age group is shown, which can be used to check if the number of infected resulting from the model is similar. It can be seen that the age group of 0 to 5 years have a low number of infected compared to the other age groups even when taking into account that this is the smallest age group. Striking is the difference between the first and second peak. In the first peak, especially 65 to 80 years have a high number of positive tested individuals compared to the other age groups, but in the second peak, this is overtaken by 17 to 25 years and 25 to 35 years, who have a high number of infections, but a low hospitalization risk. Both peaks have a high number of positively tested in the age group of 50 to 65 years. It has to be taken into account that older age groups, who are more at risk, test more often. While younger age groups, who, on average, get less sick from COVID-19 and are dependent on their parents, test less often.

Figure 56 shows the number of hospitalizations per age group in the Netherlands, which also includes the small number of Dutch citizens who were transferred to German hospitals when the Dutch IC could not handle a large number of COVID-19 patients. The number of hospitalizations is very high in March and April; this is mainly caused by the fact that there was still a lot unknown about the virus and individuals were admitted to the hospital when it was not always necessary. For this graph, only the older age groups are used, as the number of hospitalizations in the age groups, 0 to 17 years was very low and often zero. The order in the age groups with the most hospitalizations does not seem to change throughout 2020.

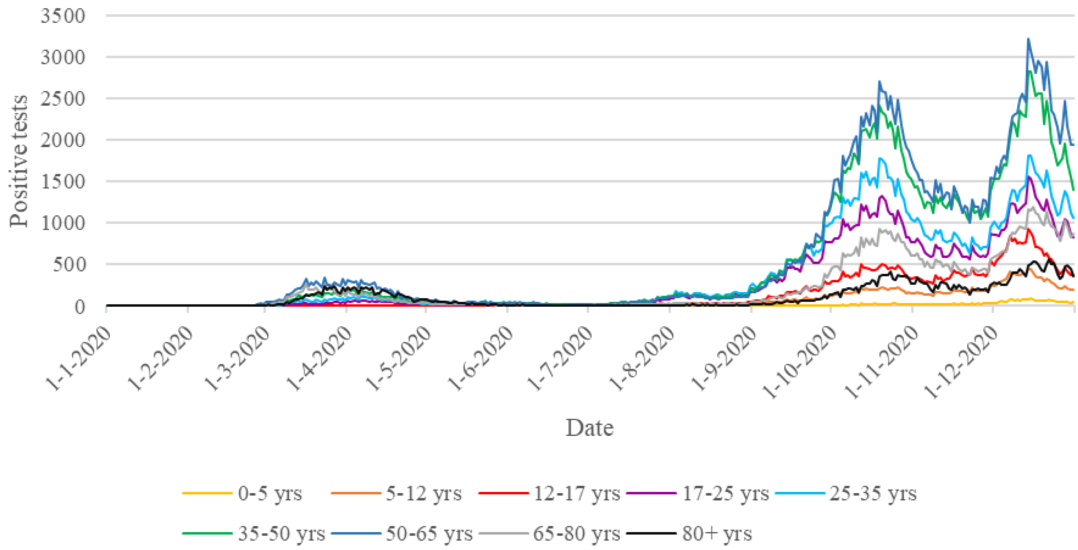

Figure 55. Positive tested in the Netherlands per age group each day in 2020 (data source: RIVM[6], 2021). Note: in this thesis, all age groups include the lower bound, but exclude the upper bound: e.g., 0 to 5 months means 0 ≤ age < 5 months.

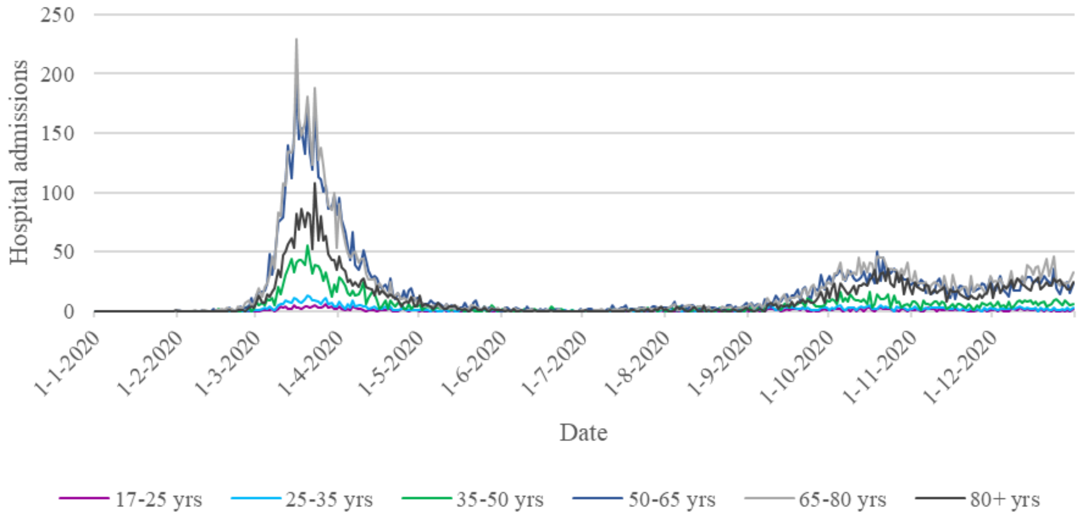

Figure 56. New COVID-19 hospital admissions in the Netherlands per age group each day in 2020 (data source: RIVM[3], 2021).

Figure 57 and Figure 58 are graphs created from running the model. The graph can give insight into the size of the age groups. Most differences are in the first peak and in case of the number of infected the ages 12 to 17 years, 25 to 35 years and 35 to 50 years are too high (note: in this thesis age groups include the lower bound but exclude the upper bound, i.e. 12 to 17 years means 12 ≤ age < 17 years). Meanwhile, in the age groups 50 to 65 years, 65 to 80 years and 80+ years the number of infected is too low compared to the other age groups.
As opposed to the number of infected, the number of hospitalizations does not influence the model because it is calculated from the number of infected. In other words, the number of infected can influence the hospitalizations but not the other way around. There are especially a lot of hospitalizations in the age group 65 to 80 years and 50 to 65 years and after that the age group 80+ years and 35 to 50 years. Changes need to be made in the age group of 35 to 50 years, which have a significantly higher number of hospitalizations than predicted. The age groups 65 to 80 years and 80+ years have a low number of hospitalizations. This is

because the model contact rates indicate that they have relatively less contact with other people, they participate less in GAET and VT and do not participate in job commuting at all. When trying to change the number of infected individuals and hospitalization in the age groups 35 to 50 years, 65 to 80 years and 80+ years by changing several variables very little happens and the other age groups are affected as well, which does not make the model produce better results. Eventually, it was decided that due to the many variables influencing the other age groups as well as the other variables, it would be better to keep the model like this, because it would make this part of the calibration too time-consuming.

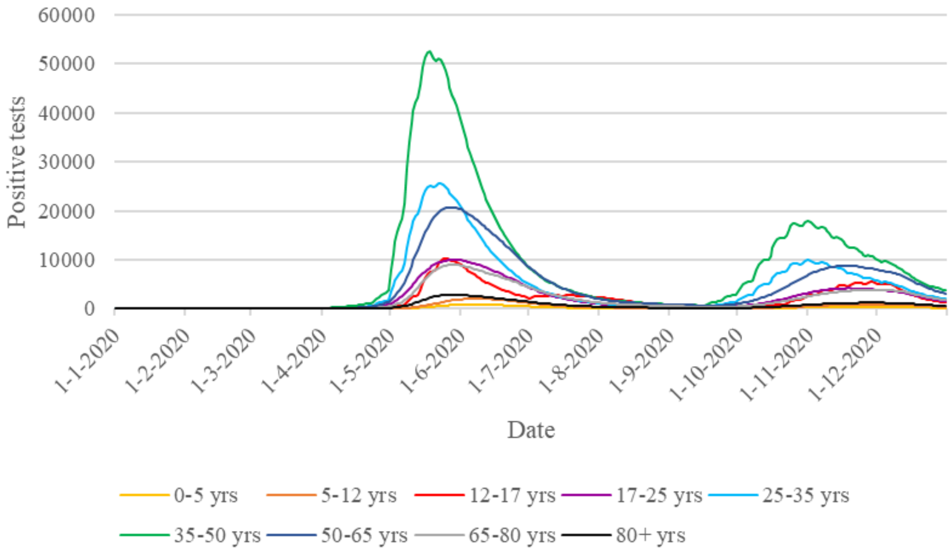

Figure 57. Positive tested per age group each day in 2020 simulated in Netlogo.

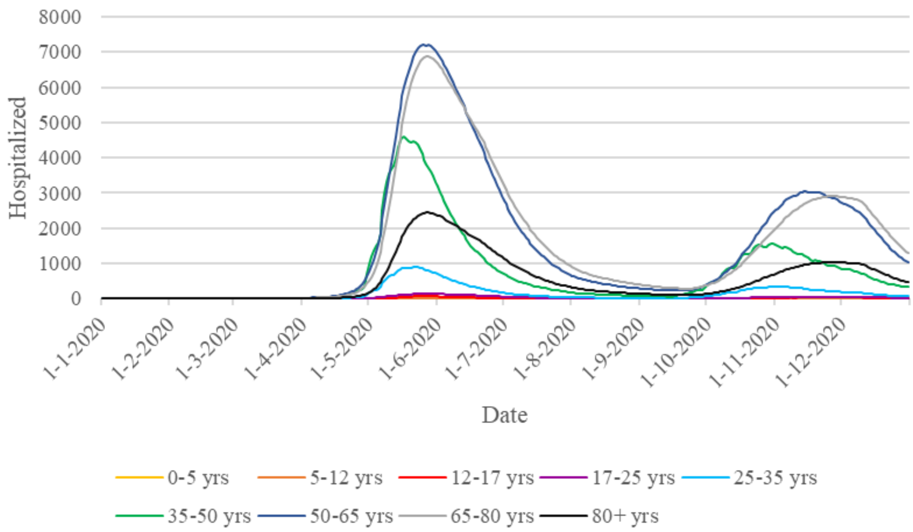

Figure 58. Hospitalized individuals per age group each day in 2020 simulated in Netlogo.

5.4.4 Infectious period

The exact data on the infectious period is lacking and is estimated to lie between 6 to 9 days (Hu et al., 2020; Rijksinstituut voor Volksgezondheid en Milieu, 2021). Therefore, the infectious period in this calibration will differ between five to nine days. Figure 59 & Figure 60 show the number of infected and the reproduction number change when the infectious period is adjusted. If the infectious period is lowered the number of infected and the

reproduction number's peaks lower as well. Furthermore, the graphs shift to the right, which indicates that the outbreak starts later. A infectious period of 5 days is the least suitable, because the peak is far too late in the year and no second peak is visible. Moreover, the R_0 does not reach 2.0 at all, which the R_0 does in the RIVM data.
In Figure 60 the peak of the R_0 is around 2.0 for an infectious period of 6 days, which is correct according to the findings of the RIVM (Data source: RIVM[4], 2020). An infectious period of 6 days is also the best fit with the guidelines of the LCI (Rijksinstituut voor Volksgezondheid en Milieu, 2021). The LCI calculate with an average infectious period of 6 days. In addition, the number of infected individuals is lower and therefore more in alignment with the real data. The disadvantage is that the beginning of the outbreak starts too late, in the next section this is improved by adjusting the start of the outbreak date.

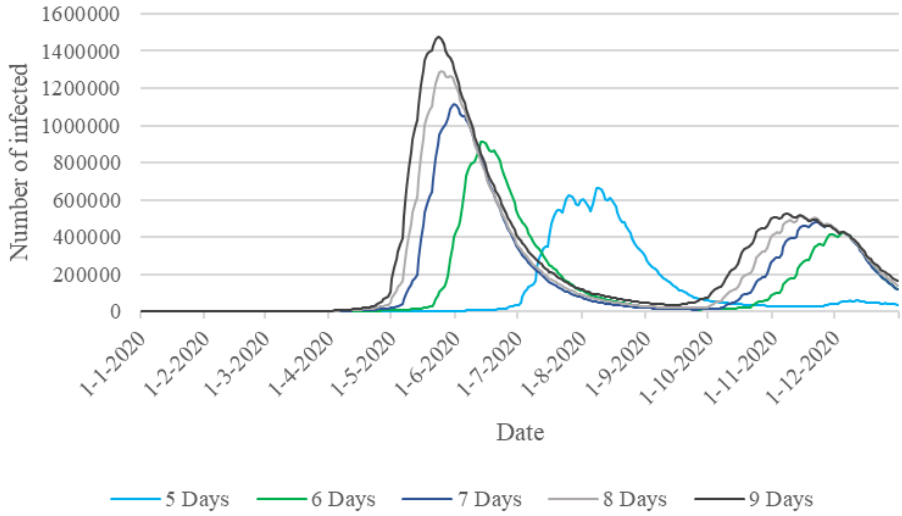

Figure 59. Influence infectious period on the number of infected simulated in Netlogo.

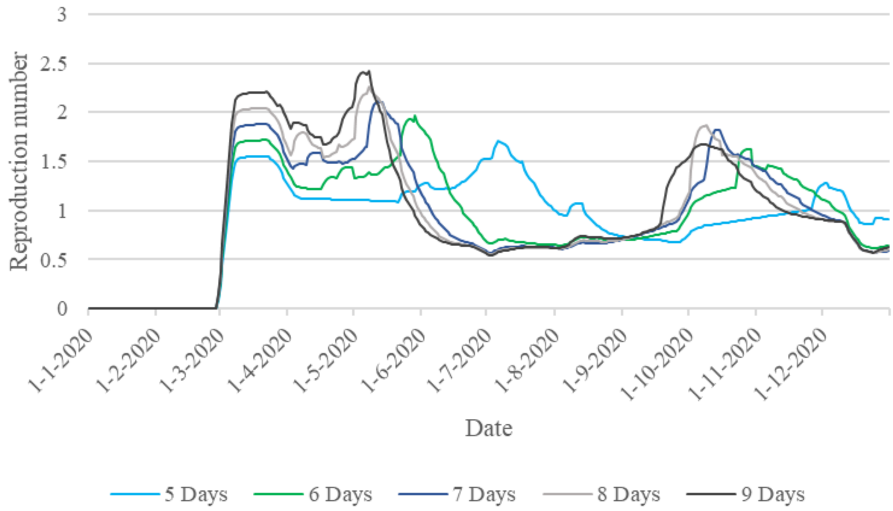

Figure 60. Influence infectious period on the reproduction number simulated in Netlogo.

5.4.5 Day of the outbreak

To finish the calibration, the research will dive deeper into the day of the outbreak. The first known COVID-19 infected individual was found in Tilburg on the 26th of February 2020 (Day 57), but it is assumed that more infected individuals were already present the week

beforehand. Additionally, this model also assumes the virus outbreak started at one point: Tilburg, while in reality there were probably more infected individuals in various municipalities. In the model, the virus takes time to let the virus spread from Tilburg to other municipalities, which causes the virus to stay a long time in Tilburg, which does not contribute to the spread and increase in the number of infected individuals in the rest of the Netherlands. Although the solution seems simple: lowering the threshold for the virus to spread to other municipalities, would cause the virus to spread too fast to all the municipalities of the Netherlands, causing an excessively high R_0. Therefore, it is decided to lower the day of the outbreak to the 1st of February 2020 (32 days). With this, the starting points of the virus in the south of the Netherlands are simulated simply by the spread of the virus from Tilburg. This does cause the virus spread within Tilburg to not be accurate.
Figure 61 shows the influence of the day of the outbreak on the number of infected individuals and the R_0. By changing the day of the outbreak the peak of the number of infected individuals is somewhat higher and starts more than a month earlier. Similar to the number of infected, the peak of the R_0 is also slightly higher and starts earlier. Striking is that the R_0 peak of the outbreak in Figure 55 is much more stretched, which is also visible as a slightly wider peak for the number of infected individuals. The differences of almost two months in the peaks of the number of infected individuals is a result of the extra time the virus spread before the first lockdown happens on the 16th of March 2020 (Day 77), which causes a higher spread rate.

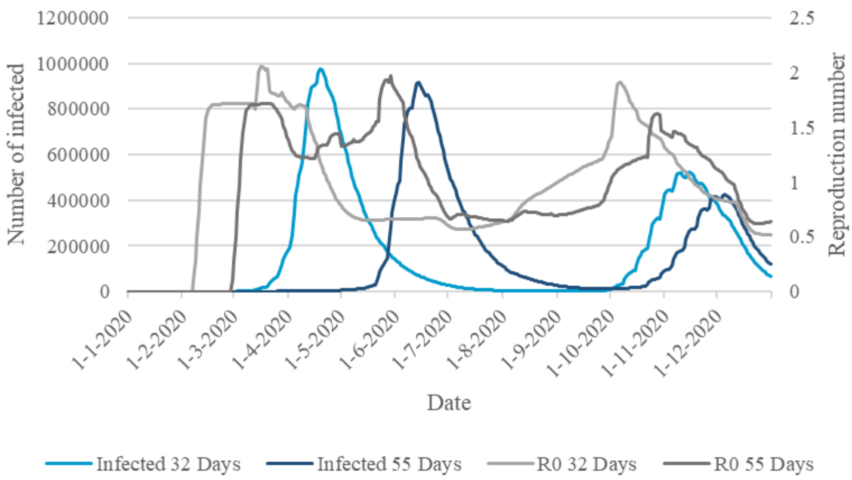

Figure 61. Day outbreak and the number of infected individuals vs. the reproduction number simulated in Netlogo.

In Figure 62 the calibrated data from the Netlogo model is compared to data from the RIVM and the LCPS. It can be seen that the R_0 graph's first peak as created by the Netlogo model is too wide. Nevertheless, it must be taken into account that the R_0 was not tracked by the RIVM before the 16th of February, thus the start of the graph is quite abrupt. Furthermore, the number of hospitalized is around three times as high as indicated by the LCPS.
To take another look at the comparison of the graphs in Figure 63 the data of the LCPS and RIVM is shifted a month. This does seem to fit the model much better if looking at the decline in the R_0 in April and the rise in October. Bear in mind that the flat area in February at the start of Netlogo R_0 graph only consists of the rise of infected in Tilburg itself and no other municipalities. If the rise in infected individuals in Tilburg is high enough it causes the spread to other municipalities, which is visible in the graph as a change in the $R_{0:}$ the line goes from a flat area to a small peak. As it is unlikely that the virus would stay in one municipality for a

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long time it could be reasoned that this part of the graph should not or only partly be included. This would make the graph already much more similar to the RIVM data. The hospitalizations are shifted too much to the left but still fit quite well. This shift, will not be used in the rest of the research but can give the reader a better insight into the fit of the Netlogo data into existing COVID-19 data.

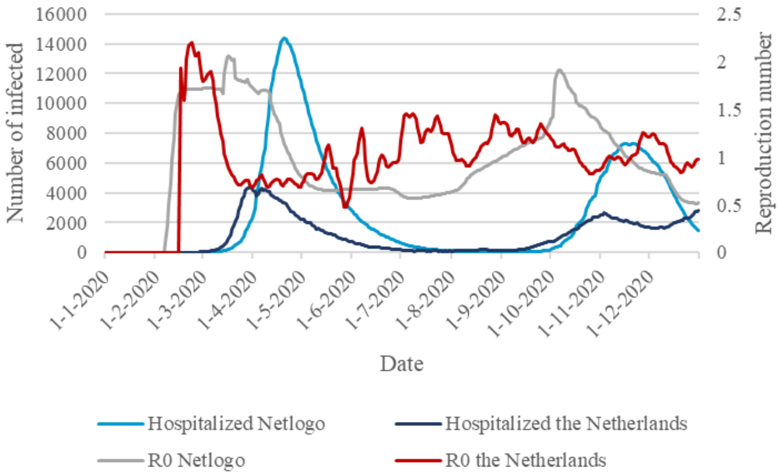

Figure 62. The number of hospitalized individuals and the reproduction number of the Netlogo model compared to LCPS and RIVM data of the Netherlands (LCPS, 2021, RIVM[4] 2020).

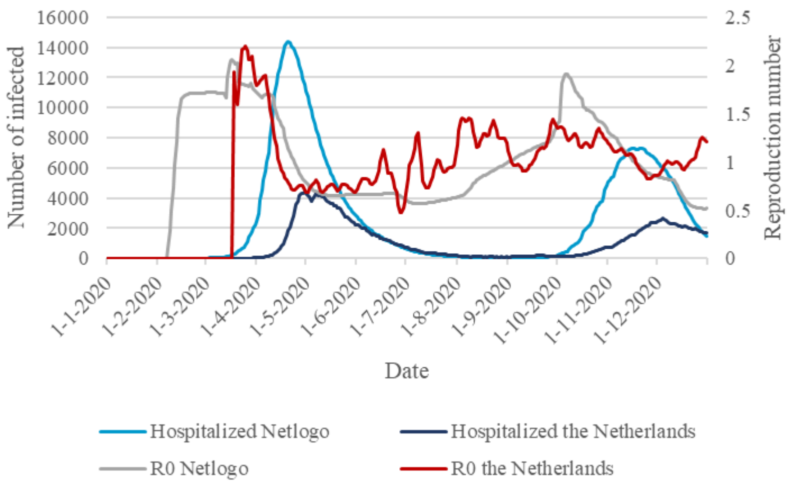

Figure 63. The number of hospitalized individuals and the reproduction number of the Netlogo model compared to LCPS and RIVM data of the Netherlands (LCPS, 2021, RIVM[4] 2020).

5.4.6 Conclusion

There are many variables to take into account, which makes it very difficult to calibrate the model. The same goes for the current studies on COVID-19, there are still many uncertainties regarding for example the infectious period, the actual number of infected in the Netherlands and the spread of the virus. Although the model does not completely coincide with reality, the model now shows the most similarities, as is currently possible in the model in terms of time and capacity.

6. ANALYSIS AND RESULTS

This chapter discusses the three scenarios that are implemented. The choice for these scenarios was made based on the most heard arguments for an appropriate COVID-19 response on a national level, as there was a lot of discussion on what the best response to COVID-19 was and still is. The government put forth a Roadmap, but at times deviated from the Roadmap due to societal pressure. The main critics of measures based their arguments on either an economic point-of-view or on the risks per age category. Hence, it was chosen to take the economic perspective into account in an economic scenario and the perspective on the differences in risks for different age groups in an age group scenario.
The results of the updated and calibrated model for the different scenarios will be analysed and compared to the real COVID-19 data in the Netherlands. In section 6.1 the three different scenarios are discussed in detail and in section 6.2 the results of the performed analysis are discussed. By looking at the number of hospitalized, the reproduction number and the spatial diffusion of COVID-19, the impact of the different scenarios is analysed.

6.1 THE THREE SCENARIOS

In this part of the thesis, the three scenarios are described in more detail. All these scenarios will make use of school and job commuting, GAET and VT. The different scenarios were run 25 times, which lead to more stable results.

6.1.1 Roadmap scenario

In the Roadmap scenario, the Roadmap of December 2020 is used (Ministerie van Algemene Zaken, 2020f). The Roadmap scenario determines risk levels between 1-5 and determines interventions (from cautious to lockdown) based on this risk level. Figure 64 shows how the risk level is determined. The risk level is based on the number of positive tests and the number of hospitalized individuals. The risk level is the highest level reached based on these two indicators. If, for example, there are fewer than 40 new hospitalized individuals per day (caution level) and there are 150 new infected individuals per 100 000 inhabitants per week (serious level), the level of risk perceived by the government is serious (risk level 3). On the right-side of Figure 64, the lockdown is added (indicated by *), which was not part of the initial Roadmap, but is necessary for the Roadmap scenario. The risk level influences the number of commuters in the model. The higher the risk level the lower the job commuting, GAET and VT will be, due to measures taken to restrict the spread of the virus. School commuting is always normal, until risk level 5 is reached. Then, there occurs no school commuting at all. Lowering the contact between individuals and lowering commuting and travelling is the coping appraisal that arises from the risk perception.
It should be noted that all five different categories (contact matrix, school commuting, job commuting, GAET and VT), as explained in section 3.1.9, always have the same risk level in the Roadmap scenario: for example, if the risk level is on level 3, measures will be implemented corresponding to a risk level of 3 for all categories, with school commuting being the exception in that it remains at risk level 1 until the highest risk level is reached. In the other two scenarios, the risk levels per category can vary. When a category reaches a higher risk level, a measure is taken to reduce that category. Therefore, in reducing the category of job commuting from risk level 1 to risk level 5, 4 measures are taken, where each successive measure is more restrictive than the former. Similar to school commuting, for

which only one measure is implemented over 5 risk levels, there are only 2 measures implemented over the five risk levels for the contact matrix category. A limited number of contact matrices was available in the model and in the calibration process, these three contact matrices were seen to most closely resemble real COVID-19 data. This leads to a total of 2 + 4 + 4 + 4 + 1 = 15 measures, corresponding to 4 possible (successive) measures for the categories of job commuting, GAET and VT, 2 possible measures for the contact matrix and 1 possible measure for school commuting (note that risk level 1 leads to no measures), which are divided over a total of 25 risk levels.

The reduction of a category for a certain measure is determined by creating equal steps between the lowest and highest percentages for a category. The highest and lowest percentages for a category are determined by comparing the real COVID-19 data of the first and second lockdowns to the pre-lockdown data. Hence, in the pre-lockdown period, the category is at 100% (unrestricted, risk level 1), if during the first lockdown the category was reduced to for example 30% of the pre-lockdown numbers (so, 70% reduction at risk level 5), then the intermediate-risk levels become 47.5% at risk level 4 (52.5% reduction), 65% at risk level 3 (35% reduction) and 87.5% at risk level 2 (12.5% reduction). The used reductions for each category can be found in Table 10.

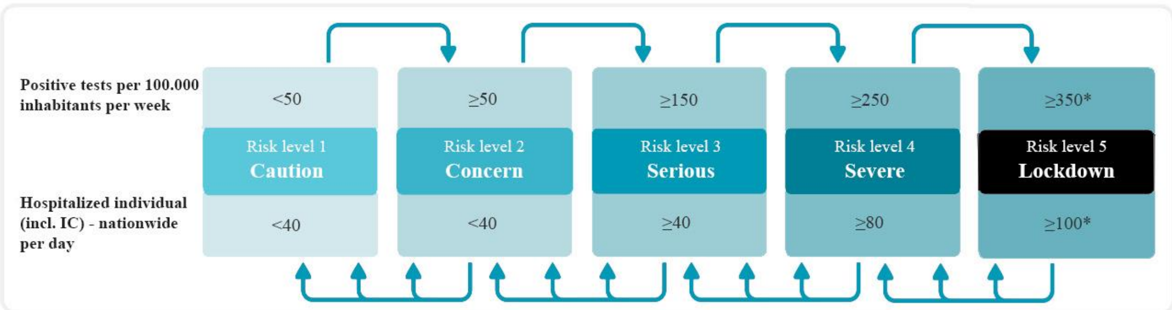

Figure 64. Summary Roadmap December 2020 The Netherlands (Ministerie van Algemene Zaken, 2020f).

	Risk level 1	Risk level 2	Risk level 3	Risk level 4	Risk level 5
Contact matrix*	2.0, 1.4, 1.0	2.0, 1.4, 1.0	1.4, 1.0, 0.8	1.4, 1.0, 0.8	1.0, 0.8, 0.6
Job commuting	1	0.8	0.6	0.4	0.2
School commuting	1	1	1	1	0
GAET †	1	0.8	0.6	0.4	0.2
VT ‡	1	0.95	0.90	0.85	0.80

** Risk level in order of 1. winter, 2. spring/autumn and 3. summer. Autumn and spring share the same contact matrix.*
† Is an estimated number. Differs per age group and non-neighbouring and neighbouring municipalities. This is an estimation based on the free time report.
‡ Is an estimated number. Differs per age group and non-neighbouring and neighbouring municipalities. This is an estimation based on the survey.

Table 10. Reductions in each category.

6.1.2 Economic scenario

The reasoning behind the economic scenario is that each measure has a certain impact on the economy. By taking the measures' impact on the economy into account, a strategy to combat the virus can be created that minimizes the impact of the measures on the economy. The economic scenario will use the same Roadmap as shown in Figure 64 to determine the overall risk level, but it differs in the choice of intervention measures. This means that the risk level per category may vary. This scenario will always choose the intervention with the lowest economic impact first. For the economic scenario, no reliable data could be identified to

identify the economical impact of the contact matrix, job commuting, school commuting, GAET and VT as defined in this thesis. To calculate the economic impact the nationwide profits and costs before and during a lockdown for each of the five categories needs to be known. As this is very specific data, which is probably time-consuming to collect and process it was decided to collect this data in another way. The creation of such data by relating the economic impact of specific reductions in the contact matrix, job commuting, school commuting, GAET or VT would be too time-consuming for this research. Therefore, an economic impact number has been assigned to each measure for each category based on the author’s reasoning and assumptions. For the contact matrix, job and school commuting, GAET and VT, these economic impact numbers are shown in Table 11. It is, for example, believed that closing schools would have the biggest impact on the economy because parents have to stay home and take care of their children instead of working. Next, reducing job commuting has a large impact on the economy, because some people could not work from home, which causes them to lose their job, which has an adverse effect on the economy. The Dutch government also provided money to citizens who lost their job because of COVID-19. On the other hand, if a job allows individuals to work from home it could also provide opportunities for the employer, as it could save them costs on for example electricity, water, office supplies and office space. The ratings for GAET are higher than visit travelling because it is believed that more money can be gained by having events and gatherings, than by visiting someone at home. Based on the assigned economic impact numbers, the contact, commuting and travelling measures are ordered, with an economic impact number of 1 meaning low impact, while an economic impact number of 10 means a very large impact on the economy.
The model will then implement measures via the contact matrix, commuting and travelling. Measures are based on the risk levels, which were also used in the Roadmap scenario. In the economic scenario, when the overall risk level is increased from risk level 1 to risk level 2, three new measures are implemented, from risk level 2 to risk level 3 four new measures are implemented, from risk level 3 to risk level 4 three new measures are implemented and from risk level 4 to risk level 5 five new measures are implemented, leading up to a total of 15 measures over 25 risk levels (5 per category). Which new measures are implemented is no longer restricted to one measure per category: the measures with the lowest economic impact number from Table 11 are implemented first. If two measures have the same economic impact number, the measures are implemented in the following order: contact matrix, job commuting, school commuting, GAET, VT measures. So the contact matrix measure with economic impact number 4 is implemented before the GAET or VT measure with economic impact number 4. The order of the measures based on the economic impact can be changed within the text file in the model’s map and when rerunning the model a new order is created and the order is not fixed in the Netlogo code.

Measures implemented on:	Risk level 1	Risk level 2	Risk level 3	Risk level 4	Risk level 5
Contact matrix	1	3	4	5	6
Job commuting	1	5	6	7	8
School commuting	1	7	8	9	10
Gathering and event travelling	1	4	5	6	7
Visit travelling	1	3	4	5	6

Table 11. Economic impact numbers for the measure per category per risk level (1 = low impact, 10 = high impact).

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6.1.3 Age scenario

The reasoning behind the age scenario is that certain age groups are more at risk to the virus than others. Therefore, measures should be taken to reduce infection in certain age groups. This can lead to a strategy to combat the virus in which certain age groups have more restrictions, while others are less impacted by measures to restrict the virus spread. For example, when the number of infections is high for the age category 65-80 years old, universities can stay open as there are few students in this age group.

For the age scenario, no reliable data could be identified to relate the impact of implementing a measure on one of the five categories (contact matrix, job commuting, school commuting, GAET, VT) to a specific age group only. Therefore, similar to the economic impact number an age group impact number was defined based on the author's reasoning and assumptions. The age group impact numbers are based on several separate runs with the model for the job commuting, school commuting, GAET and VT, and resulted in Table 12. When the number of positive tests of a certain age group is high new measures are implemented on the job commuting, school commuting, GAET or VT, depending on which type of travel influences the number of infected in the age group the most. The order of the measures thus depends on the number of positive tested individuals in each age group. The transition from risk level 1 to risk level 2 per age group occurs when there are ≥25 infected individuals within the age group per 10 000 people of that age group; risk level 3 occurs when the number of infected individuals within the age group per 10 000 people of that age group is ≥75 infected individuals; risk level 4 when ≥125 out of 10 000; risk level 5 when there are ≥175 out of 10 000 infected individuals within the age group. The infected individuals, in this case, are individuals that have tested positively on COVID-19. Measures implemented on school commuting are often avoided by the government as the age group of 12 to 17 years has a relatively low number of positive tests in 2020 compared to the older age groups and education is seen as very important for the development of children. Furthermore, measures on school commuting only apply to the age group of 12 to 17 years. The influence of the contact matrix, job commuting, school commuting, GAET and VT is hardcoded within the Netlogo code due to time constraints. This means that it cannot be adjusted by changing a table, the values need to be manually adjusted inside Netlogo itself, which is more time-consuming to vary.

Measures implemented on:	0 to 5 yrs	5 to 12 yrs	12 to 17 yrs	17 to 25 yrs	25 to 35 yrs	35 to 50 yrs	50 to 65 yrs	65 to 80 yrs	80+ yrs
Contact matrix	x	x	x	x	x	x	x	x	x
Job commuting	2	2	1	2	3	3	2	1	1
School commuting	1	1	3	1	1	1	1	1	1
Gathering and event travelling	2	2	3	2	1	2	2	2	1
Visit travelling	1	1	1	2	2	3	2	2	2

Table 12. Age group impact number that gives a measure for the impact of job commuting, school commuting, GAET and VT measures within an age group (1 = low impact,2 = moderate impact, 3 = high impact on age group).

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6.2 RESULTS SCENARIOS

This section discusses the results of the performed analysis. The impact of the Roadmap (6.2.1), economic (6.2.2) and age scenario (6.2.3) are analysed by looking at the number of hospitalized, the reproduction number and implementation of measures and comparing it with the outcomes of the modelled scenario. In the last section, the different scenarios are compared to each other and with real COVID-19 data. The last section also includes the spatial diffusion results.

6.2.1 Roadmap scenario

Reproduction number

The first output to look at is the reproduction number, which is going to be compared to the real reproduction number in the Netherlands. The maximum R_0 for the Roadmap scenario is 2.05 and the minimum after February is 0.53. What is striking is that the first peak is stretched and lower than the peak of the real R_0 data. Afterwards, a decline is visible in both lines, of which the decline for the R_0 of the Roadmap Scenario is lower for a longer period. Thereafter, a peak is visible in the Roadmap line, which is not there according to the real R_0 data from the Netherlands. On a side note, this shows that the calibration performed in section 5.4 does not result in an expected outcome in terms of the shape of the graph. But it should be mentioned that the R_0 data from the RIVM starts from 16 February 2020, but the reproduction number was not recorded before that date, therefore the peak of the R_0 of the Netherlands should be more stretched than that it is in this graph. If the line of the R_0 from the Netlogo model would start a month earlier it could better fit the real R_0 data.

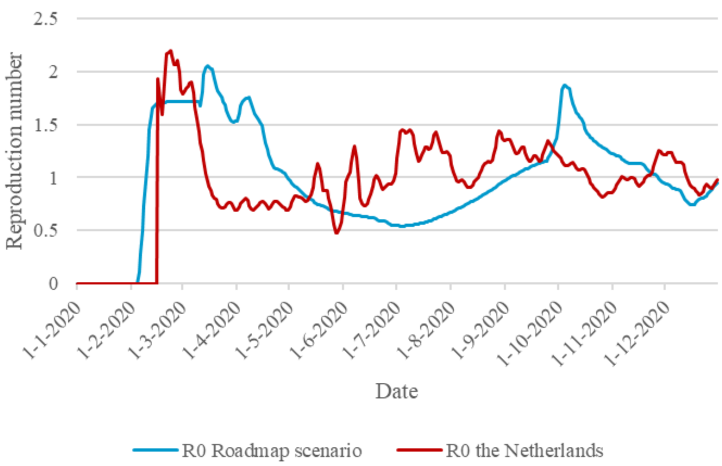

Figure 65. Reproduction number simulated in Netlogo with the Roadmap scenario and the reproduction number as recorded by the RIVM (data source: RIVM[4], 2021).

Number of hospitalized individuals

Figure 65 shows the number of hospitalized individuals. Due to very low numbers of hospitalized individuals in the age groups 0 to 5 years, 5 to 12 years, 12 to 17 years and 17 to 25 years are not included in the figures. The fact that these age groups have a low number of hospitalized individuals is a good sign, as this provides evidence on how the model aligns with the hospitalized individuals in these age groups as shown by the RIVM (data source: RIVM[3], 2021).

Figure 49 (on page 70) showed the hospital bed occupation numbers. When these are compared to the number of hospitalized as calculated in the Roadmap scenario (Figure 66), it can be observed that the first peaks of all age groups together are 3.5 to 4.0 times higher than

the hospitalizations in Figure 49. Additionally, all the peaks appear around a month later than indicated by the LCPS. Although the shape of the graph is quite similar, it must be taken into account that the calculation in the Netlogo model does not incorporate the longer admissions times in the first half-year, due to the little knowledge about COVID-19 available at the time. Infected individuals on average spent less time in hospital as the pandemic continued since there is more knowledge available on how to treat COVID-19 effectively over time. As a result, the number of hospitalized individuals in a second lockdown should be slightly smaller than in a first lockdown in the model its outcomes.
When comparing the number of hospitalized as calculated by the Netlogo model in the Roadmap scenario (Figure 66) to the number of new hospitalizations per age group as counted by the RIVM (Figure 56), there is a mismatch between the model and official data. The simulation (Figure 66) shows a higher number of hospitalizations than the RIVM data. One reason could be that the model shows hospitalized individuals per day, while the RIVM data show the new hospitalizations only, resulting in lower numbers. The graph also does not show many small peaks, like Figure 56 shows. Furthermore, the numbers of the age group 35 to 50 years are higher than the numbers of the 80+ years age group, while in the real data the 80+ years age group has higher numbers than the age group of 35 to 50 years. When looking at the proportions of all age group graphs, the age group of 80+ years should be slightly higher and the age group of 35 to 50 years should be approximately three times smaller.

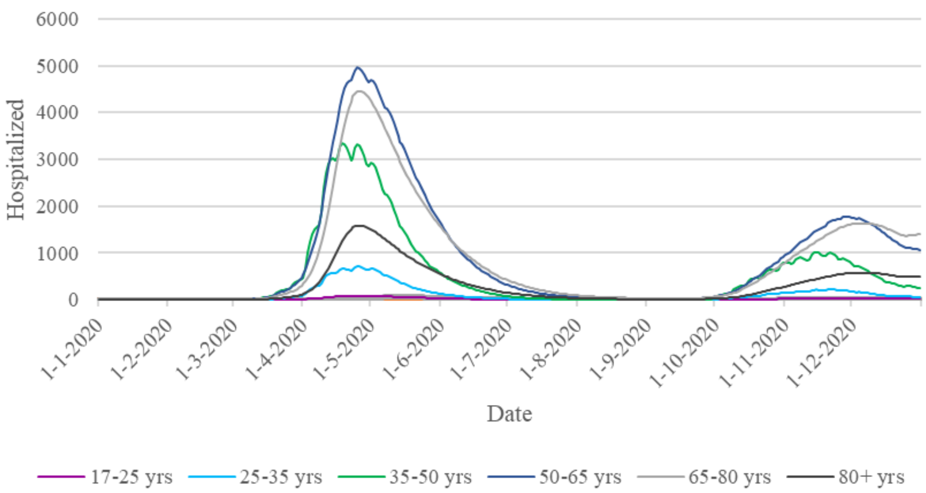

Figure 66. The number of hospitalized individuals per age group each day in 2020 simulated in Netlogo with the Roadmap scenario. Note: in this thesis, all age groups include the lower bound, but exclude the upper bound: e.g., 0 to 5 months means 0 ≤ age < 5 months.

Implementing measures
The graph in Figure 67 helps us to better understand what must be sacrificed to lower the $R_{0,}$ and thus the number of infected individuals and hospitalizations in the Netherlands. As the model runs 25 times and the average is calculated, the graphs do not always display the seriousness of the measures as they were implemented in the Netlogo model. For example, in the Netlogo model, it is only possible for schools to be completely open (100% school commuting) or closed (0% school commuting). As an average of 25 runs is used, the exact moment in time in which for instance the measure of closing schools is implemented can differ. Therefore, in the graphs, school commuting may be only participated in for 80% at an instance of time, if at that moment in time 20 out of the 25 runs that were used to calculate the average had implemented the measure of closing schools. In the graphs the commuting or travelling, before the COVID-19 outbreak, is always indicated as being 100%, meaning that there are no measures active. The lowest possible participation occurs when the heaviest

measure is implemented per category and the lowest possible participation, differs per category, as seen in Table 10. In the case of VT, this seems only to be 80% on average due to the way the travelling is coded, but in reality, this is much lower (near 20%).

In Figure 67 the travelling and job commuting is shown. There are two periods in which commuting and travelling are reduced the most: From March to May and October to December. The visit travelling is identical to job commuting, which is expected as both categories make use of the same reductions (Figure 64). The graph is fluctuating a lot, which is caused by measures being able to change daily, based on the number of positive tests and hospitalizations on that day.

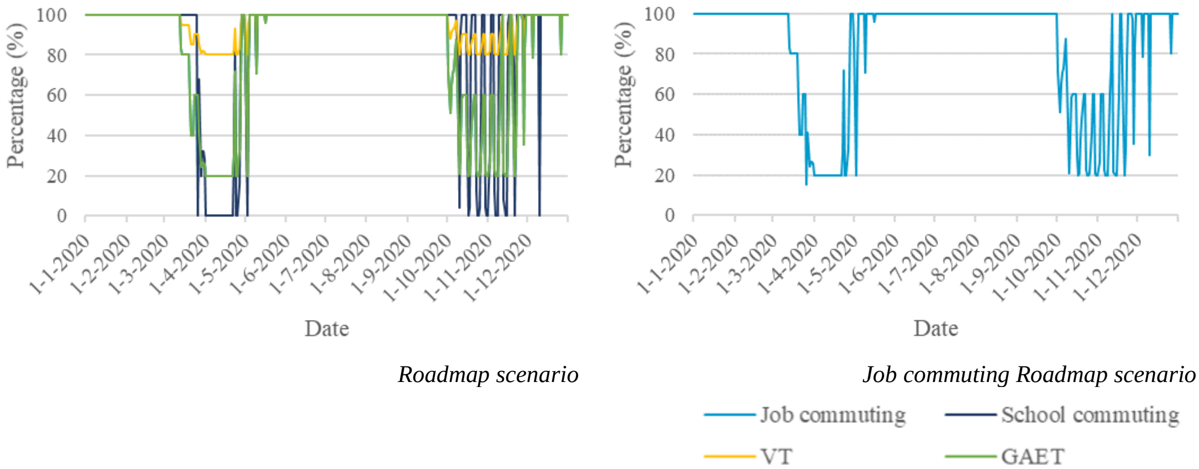

Figure 67. The measures implemented in the Roadmap scenario as simulated in Netlogo.

6.2.2 Economic scenario

Reproduction number

The by the RIVM (data source: RIVM[4], 2021) reported reproduction number shows a lot of similarities to the reproduction number produced by the Roadmap scenario (Figure 65). A minor difference lies in the second small peak at the start of April, which is smaller in Figure 68. Furthermore, there is a bump visible around the 1st of May and afterwards a somewhat higher peak in October, whereafter the R_0 declines less than in the Roadmap graph. The maximum R_0 for the simulation run of the economic scenario is 2.05, which is the same as for the Roadmap scenario and the minimum after February is 0.52 (compared to 0.53 for the Roadmap scenario).

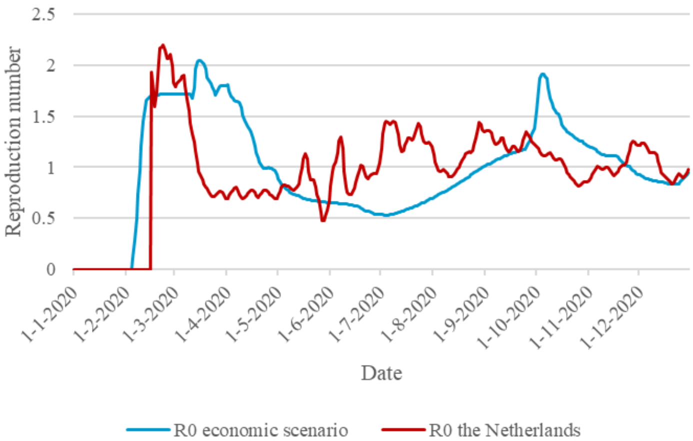

Figure 68. Reproduction number simulated in Netlogo with the economic scenario and the reproduction number as recorded by the RIVM (data source: RIVM[4], 2021).

Number of hospitalized individuals

In Figure 69, the number of hospitalization for the age group 50 to 65 years is around 500 higher, resulting in approximately 5500 at its peak. This is higher than that of the Roadmap scenario (Figure 66). All other age groups also have a higher number of hospitalized individuals, except the age group of 25-35 years. What is striking is that the peak of the age group 35 to 50 is more narrow, which indicates that there are relatively fewer hospital admissions for the age 35 to 50 years in the economic scenario in the first half-year. This graph also included two peaks, of which one is at the end of April and one at the end of November.

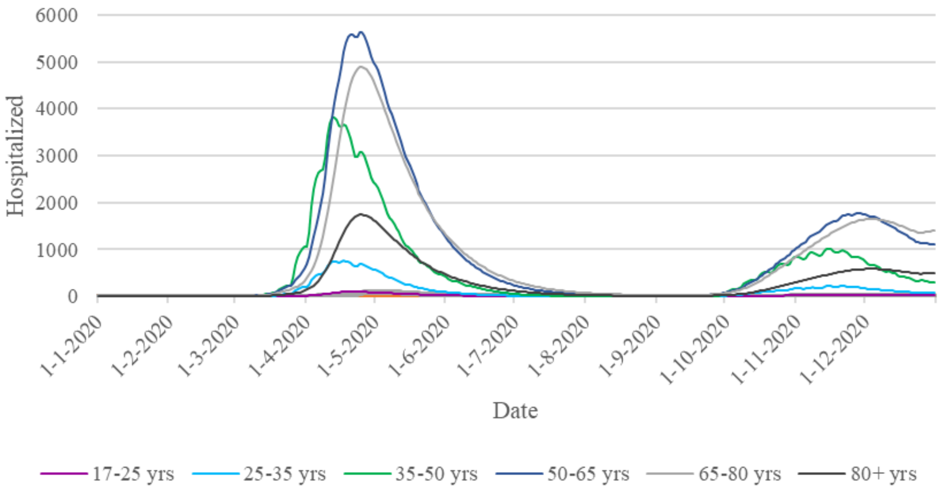

Figure 69. The number of hospitalized individuals per age group each day in 2020 simulated in Netlogo with the economic scenario.

Implementing measures

In Figure 70 the travelling and job commuting is shown. There are two periods in which commuting and travelling are reduced the most: From March to April and October to November. The commuting and travelling show similar patterns, which is expected as they will all react to the number of positive tests and the hospitalizations. It seems that these are most often either in the highest or the lowest risk level and not often in between. The graph is fluctuating a lot, which is again caused by measures being able to change daily based on the number of positive tests and hospitalizations on that day.

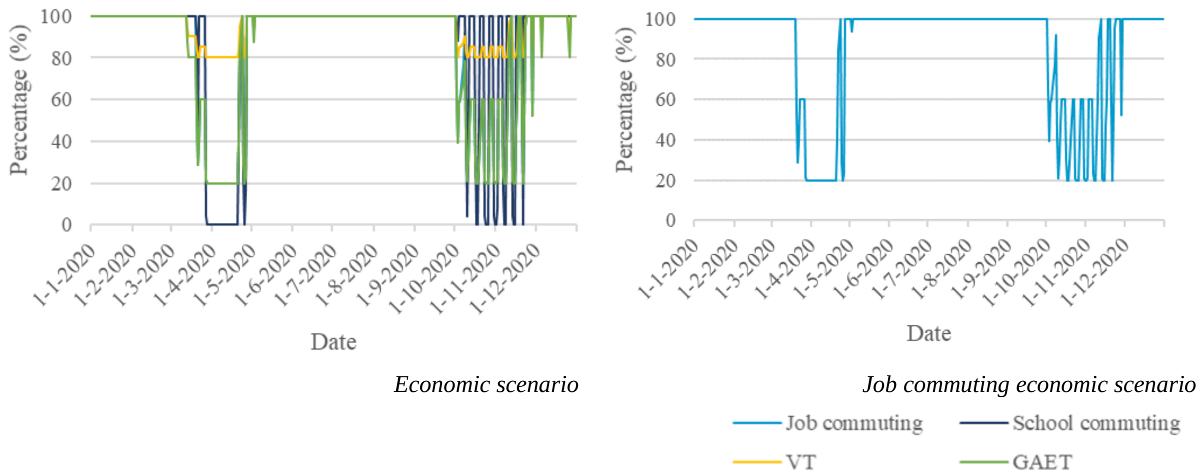

Figure 70. The measures implemented in the economic scenario as simulated in Netlogo.

6.2.3 Age scenario

Reproduction number

The reproduction number simulated in Netlogo with the age scenario and the reproduction number as recorded by RIVM (Figure 71) is very similar to the economic scenario graph (Figure 68) and are therefore only discussed shortly. The maximum R_0 for the age scenario is 2.05 and the minimum after February is 0.52, just like the economic scenario. This graph also shows two peaks, just like the others. Further comparisons will be discussed in section 6.2.4.

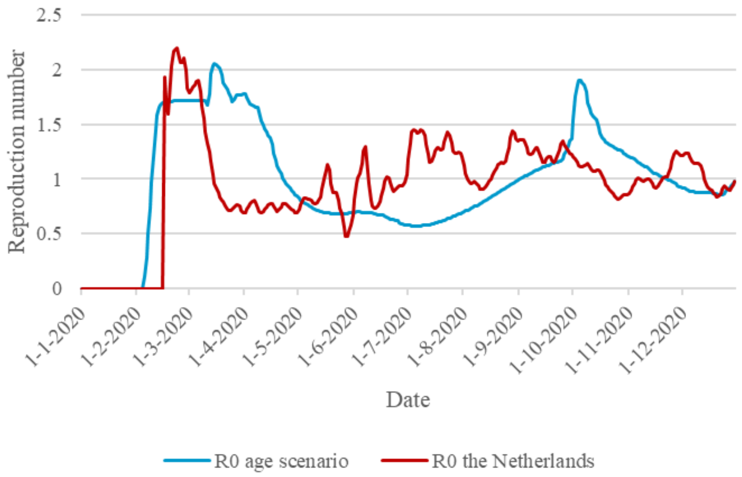

Figure 71. Reproduction number simulated in Netlogo with the age scenario and the reproduction number as recorded by the RIVM (data source: RIVM[4], 2021).

Number of hospitalized individuals

The number of hospitalized per age group each day in 2020 simulated in Netlogo with the age scenario (Figure 72) is very similar to the economic scenario graph (Figure 69), and therefore only discussed shortly. The maximum number of hospitalizations for the age scenario is 2.05 and the minimum after February is 0.52, just like the economic scenario. This graph also shows two peaks, just like the others. Further comparisons will be discussed in section 6.2.4.

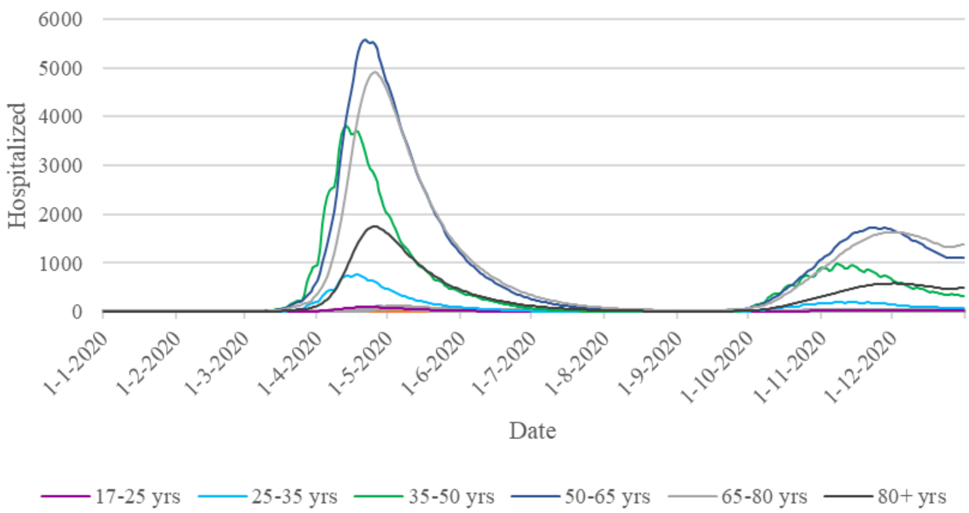

Figure 72. The number of hospitalized individuals per age group each day in 2020 simulated in Netlogo with the age scenario.

Implementing measures

In Figure 73 the travelling and job commuting is shown. There are two periods in which commuting and travelling are reduced the most: From March to April and October to November. After April the job commuting and GAET phases out up to and including June. The patterns differ more in these graphs, which is expected as the order of measures changes much more in this scenario. It seems that these graph lines are more often in between the highest and lowest risk level. Also, the school commuting is only changed briefly once and stays on risk level 1 most of the time, which means that school commuting is the same as before the COVID-19 outbreak. This is due to the low infections in the age group 12 to 17 years: the only age group that participates in school commuting and the age group with a low number of hospitalizations. The graph is fluctuating a lot, which is caused by measures being able to change daily, based on the number of positive tests and hospitalizations on that day.

Figure 73. The measures implemented in the age scenario as simulated in Netlogo.

6.2.4 Comparison of scenarios

Reproduction number

When comparing the R_0 of all the different scenarios they appear very similar, especially the economic and age scenario (Figure 74). This shows that the order of the measures taken in the economic and age scenario are quite similar even though they are implemented in the code rather differently. Measures implemented on school commuting are in both cases some of the last measures implemented. Another cause for similar results is the rapid growth in the number of infected, also visible as the R_0 peak in February and March, which causes most (and thus similar) measures to be implemented in order to decline the growth. Later in this section, the measures implemented by the model are discussed and the differences are visualised.

In Figure 75, the Roadmap scenario is compared with the hardcoded lockdown run. In the hardcoded lockdown run, the lockdown periods are predefined and based on the lockdown period in the Netherlands in 2020. In this case, the measures are either severe, or there are no measures implemented at all. In the case of the three scenarios, the chosen measures are a response to the number of positive tests in the Netherlands. In the case of the economic scenario, the measures in the five categories (contact matrix, job commuting, school commuting, GAET and VT) are not dependent on each other and can change depending on the importance of the category according to the ratings given. As for the reproduction number comparison of no lockdown, lockdown and Roadmap scenario with data from RIVM (Figure 75), it can be seen that the line of the R_0 for the lockdown run seems to be the best option.

However, when taking a closer look at the measures implemented, this option becomes less attractive.
In Figure 74 it can be seen that all scenarios lead to a sharper drop in the summer months compared to the real data, and a higher peak in late autumn compared to the real situation. This can be explained by the lack of individual risk perception in the model. When the number of disease cases goes down, not only the government responds with fewer restrictions, but also the general public responds by having more contacts. The opposite is the case when the number of disease cases goes up. The general public may perceive extra risk (on top of the restrictions implemented by the government) and restrict contacts more (even when there is no official control measure in place).

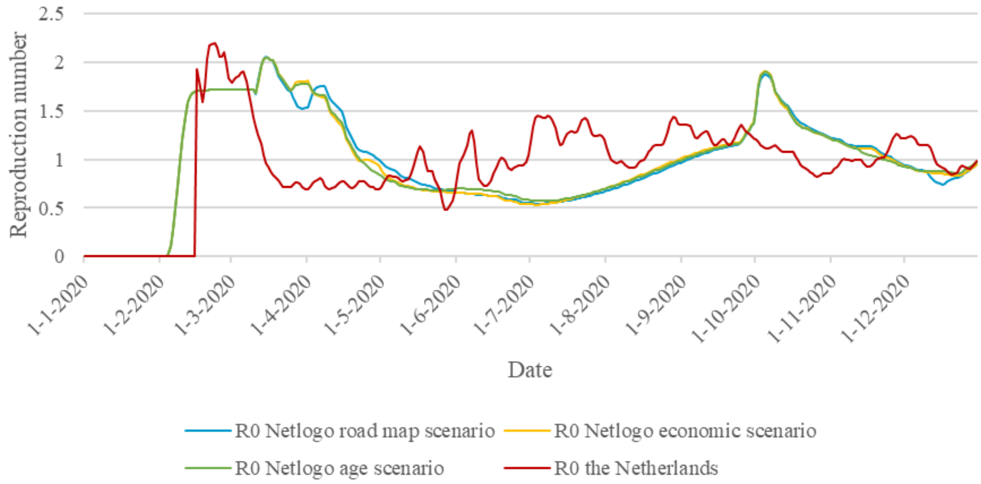

Figure 74. Reproduction number comparison of the three scenarios with data from RIVM (data source: RIVM[4], 2021).

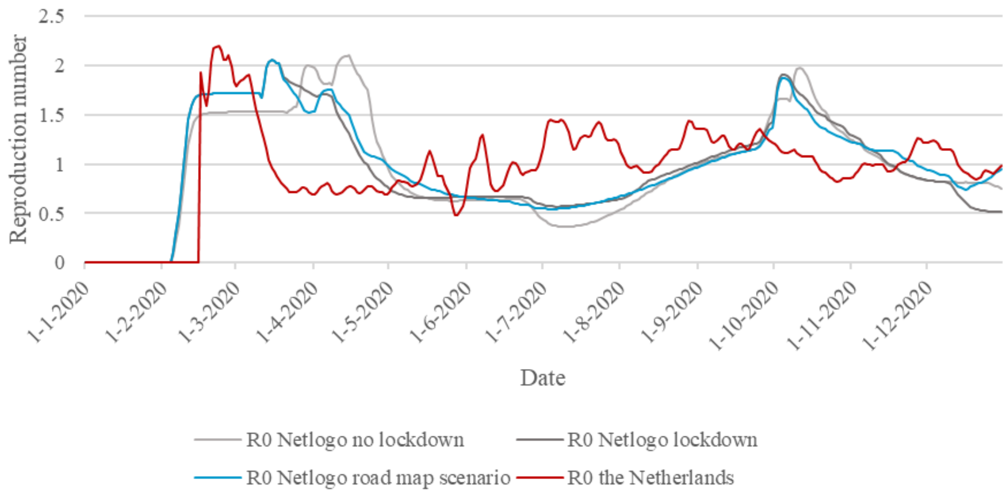

Figure 75. Reproduction number comparison the no lockdown, lockdown and Roadmap scenario with data from RIVM (data source: RIVM[4], 2021).

Number of hospitalized individuals

As the R_0 is very similar in all scenarios, it is expected that the hospitalizations graph for the scenarios is similar as well. Still, slight differences between all scenarios can be observed. Based on the R_0 values it is therefore inevitable that the graphs for hospitalizations for the economic and age scenario also feature slight differences (Figure 76). The Roadmap scenario is slightly later and lower than the other scenarios. When comparing all scenarios to the hospitalizations in the Netherlands in 2020 as provided by the LCPS (2021), it is apparent that the number of hospitalizations as predicted by the model is too high and should be at least one-third of the predicted hospitalizations to represent the hospital occupation values of 2020. This is due to the fact that the hospitalizations are calculated directly from the number of infected individuals and the number of infected individuals is invariably too high when running the model. Also, calibrating the number of infected individuals is rather difficult considering there is a lack of available data and because the model is not one hundred percent suitable for this.

In Figure 77 the Roadmap scenario is compared with the hardcoded lockdown runs and no lockdown runs with the Netlogo model. From this graph, it can be concluded that the implementation of measures does indeed impact the number of hospitalizations and halves the highest peak from 30 000 to 15 000. Although the values of the model's runs do not match that of the real values, it can be concluded that taking measures does result in less pressure on healthcare facilities.

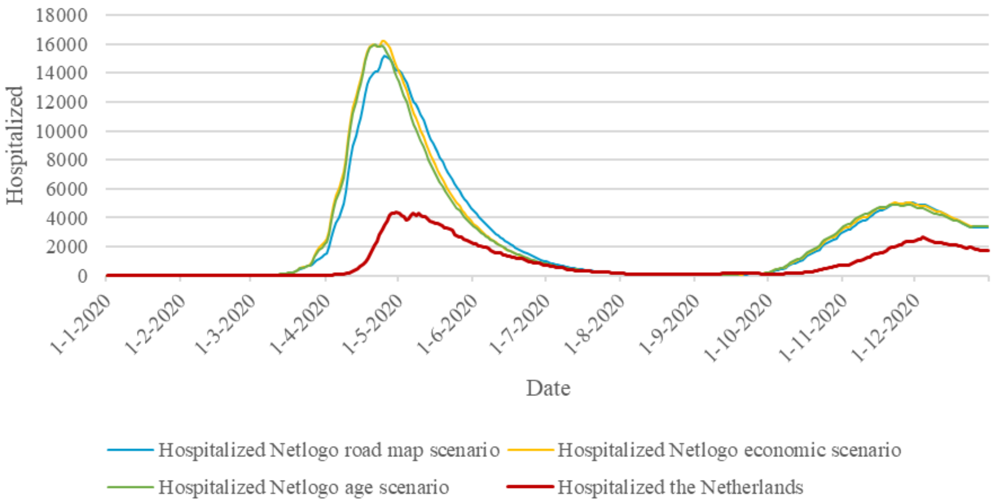

Figure 76. Hospitalizations comparison the three scenarios with data from RIVM (data source: RIVM[3], 2021).

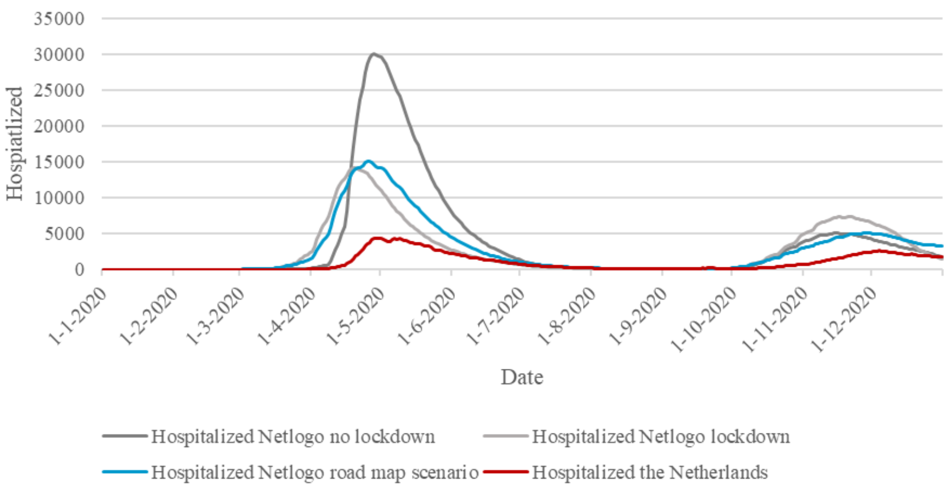

Figure 77. Hospitalizations comparison the no lockdown, lockdown and Roadmap scenario with data from RIVM (data source: RIVM[3], 2021).

Measures implemented

In this part of section 6.2.4, the measures that are implemented in the lockdown run and each scenario is compared with the other scenarios. The implementation of measures graphs (Figure 67, Figure 70, Figure 73 and Figure 78) help us to better understand what must be sacrificed to lower the R_0, and thus the number of infected individuals and hospitalizations in the Netherlands. Although the predefined lockdown (Figure 78) does result in a slightly lower number of hospitalizations (Figure 77), it also causes the population to deal with serious measures for much longer periods, compared to the other scenarios. This could eventually result in dissatisfaction of the population, which could work counterproductively, as more people will no longer adhere to the implemented measures, rendering them less effective. In addition, it causes many economic constraints. Therefore, this way of implementing measures does not pay off in the long term. It must be taken into account that these predefined measures are based on the measures in the Netherlands in 2020 and, therefore, do not necessarily fit this model perfectly. It could, for example, be better to reduce or stop the restrictions earlier or later than is indicated in this model, based on the risk perception of the government. According to the other scenarios the second lockdown is implemented too late, as the other scenarios implement the second lockdown already in October.

Figure 78. The measures implemented in the Netherlands with predefined lockdowns as simulated in Netlogo.

The model shows that it is not necessary to implement measures for a long period. In Table 13 the reductions in travelling and commuting caused by the measures are shown. In all scenarios, the job commuting measures are especially implemented in March, April, October and November. In this case, the Roadmap scenario implements relatively more and heavier measures on job commuting than the other two scenarios. School commuting restrictions are especially serious in the Roadmap and economic scenario and are almost not implemented in the age scenario. On the other hand, the restriction on VT is much less severe in the case of the Roadmap scenario, if compared to the age scenario. The GAET restrictions are quite similar in all three scenarios. It is interesting to note that the age scenarios seem to phase out the restrictions. This seems to correspond with reality, as the Dutch government does not just abolish its restrictions at once, but instead gradually reduces them.
Table 13 shows that the most difference in the reduction in commuting and travelling between the scenarios is in the school commuting and the VT. In both of these, the Roadmap scenario is very similar to the economic scenario and it seems that only in the case of school commuting, the economic scenario implements slightly more measures. At the same time, for job commuting and VT fewer measures are implemented, from which it can be concluded that the Roadmap scenario is slightly less efficient than the economic scenario. Thus, when comparing the age scenario and the economic scenario the differences are mostly in the school commuting and the VT. The economic scenario has a 12.6% more reduction in school commuting, while the age scenario has a 6.4% reduction in VT.

The government responds to the COVID-19 outbreak by choosing which measures should be prioritized based on how they affect the R_0, the number of infected individuals and the hospitalizations. But at the same time, the government needs to take into account what is best for their citizens and the national economy. Although the predefined lockdowns and the Roadmap scenario both cause a lower number of infected individuals, there are other more demanding measures, which impact other aspects, such as the economy and, in the long-term, the well-being of citizens. If the Dutch government prioritizes education, the implementation of measures like the age scenario is a good solution. Principally, because this scenario reduces the heaviness of the measures gradually. On the other hand, if the government prefers fewer measures on VT, the economic scenario would be a better choice.

	Job commuting	School commuting	GAET	VT
No lockdowns	0.0%	0.0%	0.0%	0.0%
Predefined lockdowns	-34.2%	-32.8%	-8.3%	-25.7%
Roadmap scenario	-16.6%	-13.9%	-4.1%	-16.2%
Economic scenario	-15.0%	-13.3%	-4.5%	-15.6%
Age scenario	-16.7%	-0.7%	-4.3%	-22.0%

Table 13. Commuting and travelling reductions for runs without and with lockdown and the scenarios summarized. This is the average reduction of travelling in 2020. In Appendix D the reduction for each month in 2020 is presented.

Virus diffusion

The spatial diffusion of the three scenarios was almost identical, therefore it was chosen to only add the Roadmap scenario and compare this with the scenario runs without lockdowns and with predefined lockdowns. In Appendix E-1 to Appendix E-3 the maps are visualized for 2020 with time steps of two weeks and with the help of the pattern-oriented modelling (POM) strategy (Grimm et al., 2005, p. 1; Grimm & Railsback, 2005) and the processes of diffusion description by Cliff et al. (1981) and Kuebart & Stabler (2020) the maps are analysed. It is apparent that the run without lockdown causes a faster and more intense diffusion in the sense of a higher number of infected individuals in the municipalities. On day 70 the expansion spread is visible, which signifies a spread to the neighbouring municipalities of Tilburg. In the next map, day 84, the virus spreads to the Randstad, where it causes many infected on day 98. On this day almost all the municipalities have more than 0.1% infected individuals and some even have above 10% infected individuals, partly by relocation spread, due to job commuting, GAET and VT. From June to September the virus seems to have reduced significantly. During most of this period the virus is especially present in Amsterdam. Due to Amsterdam being a large city with a large population, the virus keeps on being present within the city during the summer months. On day 280 the virus starts to spread again, starting from the Randstad, which is probably caused by the relatively high number of infected individuals in Amsterdam.

In Appendix E-2 the model run with predefined lockdowns is shown. The maps show similarities to the maps without lockdowns, but with a lower percentage of infected individuals. The spread starts relatively slower from Tilburg to the neighbouring municipalities. Already on day 70 relocation spread is visible, which is the virus diffusion to non-neighbouring municipalities. Also in these maps, the virus is mostly present in the Randstad, where most large cities are located and to a lesser extent present in the Northern, Eastern and Southern parts of the Netherlands. It can be concluded that larger cities hold the

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virus longer and therefore also spread it again to neighbouring and non-neighbouring municipalities. This would explain why the virus stays in one place, namely the Randstad, for most of the time. Similar to the runs without lockdowns, the virus reduces significantly from June to September and is present around and in Amsterdam. Next, on day 280 in October, the virus starts to spread again, from the Randstad to the other parts of the Netherlands. The virus seems to spread more to the other parts of the Netherlands, but to a lesser extent than in the runs without lockdowns. Most municipalities have >1% to ≤5% infected individuals in their population, which is much higher than the RIVM figures demonstrate. At the end of December the number of infected lower again.

If looking at Appendix E-3 at the Roadmap scenario, it appears that the Roadmap scenario is similar to both other runs. The spread on day 70 is slower than the spread in the run with predefined lockdowns but then catches up again on day 84, where expansion spread as well as relocation spread is visible. Afterwards, the virus spreads to the Randstad, where it mostly present (in orange) in the larger cities: Amsterdam, Rotterdam, The Hague and Utrecht. The virus does spread to the North, East and South, but not to the extent as it spread to the Randstad and North-Brabant, although some larger cities, like Groningen, Enschede, Maastricht and Leeuwarden do have relatively more infected individuals than other nearby municipalities. On day 126 the percentage of the number of infected individuals reduces again in most municipalities. And during the summer months (up to and including September) the virus is only present to a small extent in the Netherlands (<0.1%). Afterwards, it spreads from Amsterdam to the surrounding municipalities to the other parts of the Netherlands. The spread is not as intense as the first wave but seems to reaches more municipalities, which were not hit in the first peak. The virus spread in the Roadmap scenario is similar to the real virus diffusion in the Netherlands in 2020: the virus starts in North-Brabant (expansion spread) and then spreads to the Randstad (relocation spread). In the summer it is relatively quiet till September (one month earlier than in the model) when new outbreaks start and the virus spreads over the whole Netherlands (data source: RIVM[2], 2021).

7. DISCUSSION AND LIMITATIONS

This section discusses the encountered problems during the research as well as the limitations found for the current model, its calibration and results.

At the moment, a few existing models include risk perception and coping appraisal on a nationwide level, like the agent-based models of Tjalma (2016) and Abdulkareem et al. (2019). By creating an agent-based model, the governmental risk perception and coping appraisal and their impact on the number of COVID-19 cases in the Netherlands can be simulated and evaluated. By examining the simulated number of infected individuals, hospitalizations, reproduction number and spatial diffusion of the model, new insight can be created into the national risk perception and coping appraisal related to the virus. By adding GAET and VT to a previous pertussis model (Tjalma, 2016), the COVID-19 model became even more dynamic and a better representation of reality. After including the seasonality and adjusting the pertussis models variables, the model is able to simulate the COVID-19 outbreak in 2020.

By comparing the three scenarios (Roadmap, economic and age scenario) it can be concluded that similarities in the government's risk perception in each scenario result in similar outcomes in terms of the number of infected individuals, hospitalizations, reproduction number and virus diffusion. However, there are rather large differences in the coping appraisal and thus the resulting implementation of measures, in each scenario. Depending on the priorities of the government, measures could be implemented in the different categories, causing variation in the measures that are implemented. This is despite the fact that the timing of implementation of most of the measures is similar in each scenario (March to May and October to December 2020). The largest difference in measures occurs in the economic and age scenario: the age scenario has schools open for almost the whole year, while the economic scenario has fewer restrictions on VT. In the age scenario, the measures are implemented based on the number of hospitalizations and positive tests in the age groups. As a consequence, measures that close schools may not be implemented often, as the age group 12 to 17 years has a very low number of hospitalizations and positive tests. Still, this does cause measures on VT to be prioritized, as VT affects the number of hospitalization and positive tests in many age groups.

This research can assist decision-makers in their awareness of the order in which certain measures need to be implemented to reduce the spread of COVID-19. More targeted approaches on the age groups could help to contain the outbreak while minimizing consequences for low-risk age groups. For example, lowering job and school commuting directly affect the number of infected individuals in the age group of 65+ years, who do not go to school and (in the case of the model) do not go to work. Even though it became apparent that the predefined lockdown caused the least number of infected individuals, it must be taken into account that this also results in less freedom for citizens because it is predicted that heavy measures would result in confusion, dismay and unwillingness in the population. What stood out is that the Roadmap and economic scenario are very similar. This could be because of the largest political party in the government in 2020: the VVD. The VVD is known for their prioritization of a strong economy and the VVD considers the government as an important influencer of the economy as it can help to support and adjust the economy. It is suspected that they used their liberal influence to create the thresholds and the order of measures in the Roadmap (used for the scenario) with a focus on the economy.

7.1 LIMITATIONS

The limitations section discusses which information remains hidden in this COVID-19 model. Later in the recommendation in section 8.1 future studies are recommended, based on the limitations as discussed in this chapter.

7.1.1 Calibration

General limitations

The biggest challenge within the research was the calibration based on the base model and the model with the predefined lockdown, due to the many variables influencing each other and the fact that COVID-19 is a relatively new virus for which many variables are still unknown, undocumented or unspecified. This created a different challenge: when new data became available, existing parts of the research had to be adjusted and expanded. Moreover, the addition of GAET and VT to the model added to the already large effect the job commuting and school commuting has on the spread of the virus and the large increase of infected in the large cities, which are the centre of commuting and travelling. This made it hard to decrease the number of infected individuals produced by the model. In hindsight, this was also concluded by Tjalma (2016) in her thesis. Tjalma (2016) also experienced problems with the commuting data and since this research is built on the research of Tjalma, similar difficulties were to be expected in this thesis. Tjalma advised in her thesis to look into "…different ways of modelling movements in the Netherlands" (Tjalma, 2016, p. 71), but the addition of GAET and VT did not solve the encountered problems.

Age groups

During the calibration, it became apparent that the number of hospitalized in the age group 35 to 50 years was too high and the hospitalizations for the age group 80+ years was a bit too low (Figure 58). Unfortunately, it was not possible to adjust this correctly due to time constraints. In this case, it would also be much more logical if the age group 80+ years had more hospitalizations. This could have been adjusted by changing the contact matrix for the 80+ years group or by adjusting the calculations for hospitalizations. As there was no proof that the contact matrix and the calculations of the hospitalizations were the cause of the distortion, it was decided to leave it like it was and also because such changes would negatively influence the other outcomes. The outcomes of the calibration were sufficient to start running the model, as the results were seen to resemble reality qualitatively.

7.1.2 Model

Age scenario

Due to time constraints, it was not possible to create the initially planned version of the age scenario, in which parameters would be easy to vary. Such an approach would have improved the flexibility and adaptability of the age group scenario to new data. Instead, the age scenario of this thesis was simplified and consisted of a hardcoded order. Therefore, changes to the age scenario need to be made to the code itself, which is less desirable since it is harder to read and change than a text file that can be read by the model. Still, it gave similar and interesting results.

Following measures

It should be noted that this research assumes full compliance by Dutch citizens with all measurements implemented by the governments. In reality, resistance to measures and civil disobedience is to be expected to grow in the population. As a result, it would be expected that the effectiveness of a certain measure decreases over time. Such reduction in the number of individuals following the measures is hard to deduce from real-life data and therefore difficult to implement in the model.

Hospital admissions
Furthermore, the model does not take into account the longer hospital admission times at the start of the outbreak. Due to a lack of knowledge on how to treat COVID-19, patients often stayed at the hospital for a longer period. For this research, the average stay of a COVID-19 patient in 2020 is used.

7.1.3 Outcomes

Reproduction number
As previously discussed in Chapter 5, the reproduction number does not completely match the reproduction number in the Netherlands as calculated by the RIVM[6] (2021). This can be partly explained by the virus being isolated for more than one month in Tilburg in the model before it spread to the other municipalities. This causes a wide first peak in the R_0 (Figure 62). Additionally, the R_0 in the second peak is too high in the model, which causes a high peak of infected in October and November. It is interesting to note that if the RIVM data would be delayed by one month, the data would have fitted much better with the Netlogo results (Figure 63), but this is not used in the model.

Comparing the scenarios
After the calibration, the model has been run for the three different scenarios. Hereby, the model proved it was possible to model risk perception and coping appraisal to evaluate the different scenarios. With the outcomes, it was not completely possible to identify the best scenario. According to the model, predefined lockdowns and the three scenarios do have a similar effect on the number of infected individuals and hospitalizations. Also, taking measures does influence the number of infected individuals. But, by looking at the periods the measures need to be implemented, the age and economic scenario both are more attractive ways to implement measures according to the model. In this case, the government would evaluate the measures necessary for each day, which is not always feasible if taking into account the participation of the citizens. It is predicted that many changes in measures would work counterproductively for the citizens' compliance with the measures. The strong fluctuation in the measures was not the intention when creating the model. It would have been better if, when new measures were applied, these would have been applied for at least a week. However, due to time constraints, this was not implemented. Furthermore, the identification of which scenario is better also depends on the priorities of the government in terms of the impact of the measures on the population and economy. The model proved that by implementing different measures similar results can be achieved and that more measures do not always result in less infected individuals.

7.1.4 Data

Economic data
There was no specific economic data available for each of the five categories, therefore the author's knowledge is used. The economic data could be changed relatively easily within the model, so other users can implement their own economic choices.

GAET and VT data
There was also no GAET and VT data available. Therefore, it had to be created via a free

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time report (Centraal Bureau voor de Statistiek, 2021) and from a survey. Although this survey did get much more respondents than expected, it is still less reliable as not all age groups had enough respondents. As the GAET was derived from a free time report, the data had to be converted to be useful in this thesis, but this causes the data to be less specific.

Variables

Additionally, it was difficult to decide on the right infectious period as there were many uncertainties in the literature about the value of this variable. (Hu et al., 2020) their research indicated that the infectious period is 9 days, while the (Rijksinstituut voor Volksgezondheid en Milieu, 2021) uses a infectious period of 5 to 6 days in their calculations. Also, initially, the day of the outbreak was set on day 55, which was close to when the first person with COVID-19 was identified in the Netherlands, but this did not produce the expected results, because it delayed the spread to other municipalities too much. Therefore, an outbreak on the 1st of February was chosen for the model, so that the virus had enough time to spread to the other municipalities, without delaying the first peak too much.

8. CONCLUSION AND RECOMMENDATIONS

The main goal of this research was to evaluate the impact of the governmental risk perception and coping appraisal on the predicted number of disease cases for COVID-19 in the Netherlands with a COVID-19 Netlogo model. The main research question was:

How can the risk perception and coping appraisal in a COVID-19 model help to evaluate different interventions scenarios?

This question was divided into the three sub-questions, which are stated and answered below.

A. *How can the existing pertussis/COVID-19-model be remodelled?*

For the simulation of the COVID-19 outbreak in the Netherlands an agent-based pertussis model was modified and used to test the newly available virus data. The virus diffusion was simulated via a SEIR model for nine different age groups on a municipality level, while the restrictions implemented are on a nationwide level. Several adjustments were necessary to convert the Pertussis model into a COVID-19 model. The adjustments to the Pertussis/COVID-19 model were done by changing variables such as the exposed period, infectious period, recovered period and day of the outbreak. Furthermore, one start location was chosen: the city of Tilburg, where 25 infected were introduced.
The previous model only took the school and job commuting into account and did not cover leisure travel, which was divided into two categories and also contributes to the spread of COVID-19. By enhancing the older model with leisure travel, which was divided into the two categories of gathering and event travelling (GAET), and visit travelling (VT), the model provides a more realistic travel behaviour within the Netherlands, where GAET and VT also help the virus diffuse from one municipality to another. The GAET and VT were based on a survey and a free time report (Centraal Bureau voor de Statistiek, 2021) and made use of the travel data from job commuting.
The new model also takes the seasonality that plays a role in the spread of COVID-19 into account, just as the Pertussis model. Hence, the model included a functionality to adjust the use of the transmission rate (contact matrix), commuting and also the travelling. All of which could be different in the winter, spring, summer and autumn.
Most of the results were based on the number of infected individuals, the reproduction number and the hospitalizations. The calculations of hospitalizations were changed to create a better fit for the number of hospitalizations in relation to the number of infected individuals in the Netherlands in 2020. The previous model did not provide the number of positive tests, but in the current model, this was necessary to help decide the timing of the implementation of new measures. Therefore, the number of positive tests were included in the model.
The Netherlands as a whole, thus the Dutch government, was identified as the ‘main’ agent in the model. The government has the goal to react to COVID-19 by lowering the number of infected individuals by implementing measures if the total number of infected individuals in the Netherlands reaches a certain threshold.

B. *How can the governmental risk perception and coping appraisal be incorporated into an agent-based COVID-19 model?*

Changes were needed to implement risk perception and coping appraisal into the model and to test different scenarios. The adjustments for risk perception and coping appraisal were

necessary to make it possible for the main agent, the government, to assess when and which measures needed to be implemented, based on the number of infected individuals, the hospitalizations and the positive tests.
The first option in the model simulates what happens if there are no measures implemented at all, while the second option simulates what happens if there are predefined lockdowns, based on the lockdowns in 2020. Besides the options of running the model without measures and with predefined lockdowns, three scenarios are available to select within the model. One scenario is based on the Roadmap published in December 2020, which is a strategic plan of the Dutch government that identifies when and which new measures are implemented based on the number of infected individuals, the reproduction number and the hospitalizations. Although the Roadmap was developed and published, measures were never implemented in complete accordance with the Roadmap.
Two other scenarios were identified by looking at the factors influencing the timing of measures and the kind of measures that were discussed during the press conferences and in Dutch politics. Factors which the Dutch government thought were important to base their choice of measures on were the economy and the ages of the infected individuals. The economy is a strong driver in Dutch Governmental decision making. Besides controlling the number of disease cases, reducing the impact that the control measures have on the economy is an important motivation. As a result, an economic scenario was defined. This scenario evaluates what the result would have been if always the measures with the least economic impact would have been implemented first. The third and last scenario defined in this research was the age scenario. In the base model, all control measures apply to all age groups in the population. Differentiating between age groups is a strategy that was never considered by the Dutch government. The age group scenario evaluates measures per age group instead of for the total population.
In the end, five options are available to run the model: without measures, with predefined lockdowns, the Roadmap scenario, the economic scenario, and the age group scenario. In the first two options, the risk perception and coping appraisal by the government within the model were not taken into account yet, as there are either no restrictions or the lockdowns are established in advance. In the other three scenarios, the government does have coping appraisal and risk perception. The level of risk perception (risk level) depends on the number of positive tests and the number of hospitalizations. Based on this level, the coping appraisal is activated and new measures are implemented, which can cause a reduction in the transmission rate (contact matrix), job commuting, school commuting, GAET and VT. Which measures are implemented depends on the scenario. By identifying which measures are implemented within the model at what time and combining this data with the data on the reproduction number, the number of hospitalizations, the spread of COVID-19 within the Netherlands, and the impact of risk perception and coping appraisal on the reproduction number can be evaluated.

C. *What are the effects of risk perception and coping appraisal on the number of COVID-19 cases, and the spatial diffusion of COVID-19 in the Netherlands?*

First, the model was run without any measures, and with predefined lockdowns to calibrate the model. Different data sources were used for this calibration, such as the check-in and check-out data from Translink (2021), a survey and a tourism and free time report (Centraal Bureau voor de Statistiek, 2021). Furthermore, the outcomes of the model were compared with real COVID-19 data, such as the number of infected individuals, the hospitalizations and the reproduction number. Eventually, as a result of calibrating the model, the infectious period was set to 6 days and the day of the outbreak was moved to an earlier date: 1 February 2020. The outcomes of the model for the number of infected individuals and the hospitalizations were 7 to 10 times higher than the numbers published by the RIVM for 2020. The new measures did have a positive impact on the number of infected individuals. By implementing more measures, the increase in the number of infected was reduced and over time it even resulted in a lower number of infected. Similar patterns were seen for the hospitalizations, as the hospitalizations were calculated directly from the number of infected. The reproduction number also became lower when more measures were implemented.

To test the performance of the model, the three scenarios, the Roadmap scenario, the economic scenario and the age scenario, were run to simulate the risk perception and coping appraisal of the Dutch government. The scenarios were evaluated on two groups of aspects: impact on the disease cases (the reproduction number R_0, the number of hospitalized cases) and their impact on the society (the impact on travel, the risk level).

The diffusion patterns of the scenarios are all similar, and therefore this thesis only looked at the virus diffusion for the Roadmap. When comparing it to a run without any measures, it becomes apparent that measures slow down the virus diffusion and thereby result in a lower number of infected individuals and number of hospitalizations. The virus diffusion in the model is very similar to the virus diffusion in the Netherlands in 2020: the virus was first detected in Tilburg, spread to North-Brabant (expansion spread) and then to the Randstad (relocation spread). From the Randstad, the virus spread to the rest of the Netherlands. Most of the infected individuals live in large cities, and where, thus, many people can get infected in a short period of time. As a consequence, the virus remained for a longer period in such large cities. It appears from the maps that the virus was not as much present in the North, East and South of the Netherlands as to the extent it was in the Randstad and North-Brabant.
The Roadmap scenario and the economic scenario showed the most similarities in terms of measure implementation, although during a Roadmap scenario run there are slightly more measures implemented for a longer period. Comparing the economic and age scenarios the difference in measure implementation are mostly in the school commuting and VT. Which scenario is more suitable, depends on the government's priorities. If it is preferred to have the schools open for as long as possible, the age scenario would be better, as there will be no measures implemented on school commuting, such that the (low risk) age group of 12 to 17 years could go to school. If the government prefers to make it possible for people to meet others, then the economic scenario, with a lower number of VT measures, would be ideal.

8.1 FURTHER RECOMMENDATIONS

The following recommendations provide opportunities to respond to the limitations of this model (7.1) by suggesting how to handle the encountered problems in future research:

- Section 8.1.1 continues the Calibration section 7.1.1,
- Section 8.1.2 continues the Model section 7.1.2,
- Section 8.1.3 continues the Outcomes section 7.1.3
- Section 8.1.5 continues the Data section 7.1.4.

The extra section Additional recommendations (8.1.4) discusses the recommendations that could improve the research, but lie outside of the scope of this research.

8.1.1 Calibration

Due to time constraints, the calibration for especially the hospitalization of the age groups 35 to 50 and 80+ years could not be made in agreement with the COVID-19 data. Although the outcomes are not exactly as was desired, it was sufficient enough to start running the model for the results. For future use of this model, it is recommended to spend a lot of time on the calibration as the many different variables influence each other, which does make the calibration difficult and confusing. Therefore it is recommended to map the influence of the adjustments to the variables better.

8.1.2 Model

Age scenario

For future use of the model, it is recommended to update the age scenario. As due to time constraints it is a simplified version of what was planned, extra attention to this part of the model would be necessary. Changing the model so it is able to handle text files to create an order in the measures in the five categories, similar to the economic scenario, would make it easier to implement future changes to the model. If the age scenario is not used in other research, then changing it will not be necessary as it does not influence the rest of the model.

Following measures

There are also several possible future functions devised during the creation of this thesis that could improve the model. There are for example no super spreading events taken into account, even though these events do significantly contribute to the spread of the virus. The spread of viruses during religious and church gatherings could also make an interesting addition to the model, as there have been a few large COVID-19 outbreaks in church communities. This could be implemented by introducing newly infected individuals in municipalities that have had large gatherings in 2020. In case of large religious gatherings: a random municipality can be selected within the Bible Belt in which newly infected individuals are introduced. An additional research gap is the effect measures have over a longer period. It is assumed that the support for measures decreases over time. People get “tired” of the measures and will less often adhere to the rules over time. This is something that cannot be measured and is therefore difficult to implement, but this would make the model more realistic. If this would be implemented correctly, the model will show the decline of the impact of the measures and it would result in an increase in the number of infected individuals over time.

Hospital admissions

For this research, the average stay of a COVID-19 patient in 2020 is used. Although the hospital admissions change as knowledge on treatment of COVID-19 improved over time, the model does not take into account the longer admission times at the start of the outbreak. This could be changed in the model by calculating it for several periods, of which the first period, when the outbreak starts has the most hospital admissions compared to the number of infected individuals. If the hospital admissions of another country need to be used it could be easily changed on the first page of the code in Netlogo.

8.1.3 Outcomes

Reproduction number

The reproduction number does not fit the real data partly due to the virus being isolated for more than one month in Tilburg in the model before it spread to the other municipalities. In future research, the model can be adjusted so the virus spreads faster, by for example

lowering the threshold Tjalma (2016) implemented which, when the lowered threshold is reached, allows the virus to spread to other municipalities. Care must be taken with not lowering the threshold for other municipalities as well, as this would result in the virus spreading too fast within the Netherlands.
The infection rate is based on the contact matrices between susceptible and infectious people. Therefore the R_0 could also be changed by adding more options for the contact matrices. At the moment a contact matrix of 2.0 and 1.4 is available, but no contact matrix in between. A contact matrix of 1.8 could provide more options to influence the R_0 and the virus diffusion.

Comparing the scenarios
The downside of the scenarios is that the implemented measures are fluctuating a lot. It would be more logical that these measures would stay the same for at least a (or two) week(s) because the government would not change measures on a daily basis, since such changes in measures would be confusing and impractical for citizens to follow. Still, Table 13 show that measures do not need to be implemented for such a long time and that the government could change different measures, and thus their coping appraisal, based on their desires concerning the population and economy. For example, the economic and age scenario led to similar results with a different implementation of measures. It would be recommended to change the model such that measures cannot be changed on such short timescales.

8.1.4 Additional recommendations

Holiday travelling
It was originally planned to add holiday travelling to the model, but it was concluded that it would not have a large impact on the number of infected within the Netherlands. Although international holiday travelling could be an interesting addition to the model, as such travelling could create new outbreaks in different municipalities, it is rather difficult to simulate. It could also be worthwhile to include the border and cross-border issues related to health care providers in terms of COVID-19 to the model. International decisions and problems could of course influence the Dutch government their decision. If other nearby EU countries are perceiving risks and take action, the Dutch of the government is more likely to take respective action even if the situation in the Netherlands per se is perceived as calm.

Gender
Originally the SEIR data also consisted of the gender of the population. This variable was left out of the model because it is not relevant for the current research, but could easily be included in future research if corona-related epidemiological factors are proven to be gender-sensitive.

Vaccinations
This research did not include vaccinations because only the year 2020 is taken into account, during which there were no vaccinations administered within the Netherlands yet. Future research should take the influence of vaccinations on the spread of the virus with an agent-based model into account, as it could give the government more insight into their vaccination strategy. If necessary, the vaccination can easily be added, as it was already implemented to the model by Tjalma (2016).

Since there is was no data available on COVID-19 vaccinations in 2020 and as it was outside of the scope for this research, it was not implemented. However, there is still a function in the model that comes from the pertussis model. Even though this research did not focus on vaccinations, it could be interesting to implement this in the future, especially with the new knowledge on vaccines resulting from the vaccinations that have been admitted since January 2021. Research on herd immunity together with the geographical aspects could help the Dutch government to understand the diffusion of the virus once a certain percentage of the citizens get vaccinated.

Municipality level
In the initial planning of the COVID-19 model creation, municipal risk perception and coping appraisal were included in the model, besides the governmental risk perception and coping appraisal. Incorporating the municipal level was excluded from this study due to time constraints, but it could be a great addition for future research. The fact is that the government is not the only one deciding when and which measures are to be implemented. The municipality can decide on their own when to implement measures in their municipality based on the number of infected individuals, the number of hospitalizations and the reproduction number in their municipality or neighbouring municipalities. By adding the municipality as an agent a more dynamic model could be created that resembles reality more closely. As an extra addition, the model could be taken to the next level by also making the municipality influence the national government.

Pertussis model
It can be concluded that the adjustments made while converting the Pertussis to a COVID-19 model would also be beneficial to be adopted in future Pertussis modelling. The Pertussis model was missing travelling, besides job and commuting, especially for the age groups that do not participate in job and school commuting (0 to 12 years and 65+ years). By adding GAET and VT the Pertussis model could represent the reality better.

8.1.5 Data

Economic data
Extended research is necessary to identify the economic impact of the measures, so a new and more realistic order for implementing the measures in the economic scenario could be created. Such research would be difficult, as the five categories as defined in this thesis are not specified in the same way in other works and can be called by other names or included in other definitions. In many documents, GAET will be probably split into religious gatherings, cultural events (festivals, concerts, opera, dance, exhibitions), sports events and other gatherings and events. Collecting this data for GAET could be very time-consuming as it consists of many different components, which should be merged. Furthermore, it is very difficult to define the economic impact of VT, as lowering the VT does not have a high economic impact on its own, but it must be taken into account that mental health issues may arise if the number of social contacts of a person is very low. This could in the long term affect the Dutch economy because of the additional pressure on healthcare and because of the resulting large number of individuals who are unable to work. Therefore, defining the economic impact of each category and collecting the data will be very difficult.

GAET and VT data
Although the GAET and VT data is deduced from a free time report (Centraal Bureau voor de Statistiek, 2021) and a survey, in future research the researcher needs to keep an eye on whether new data exists, which could better represent the GAET and VT.

Variables

New data could reinforce this research on this relatively new virus. At the moment, many large data gaps exist, but it is expected that during the upcoming years many new kinds of research will be performed, resulting in a new variety of useful data. During the last month of the research new data was made public containing the number of IC and hospital beds taken by COVID-19 patients, which was a valuable addition to the calibration and the results, but it did result in some late adjustments. This research could especially be reinforced by more precise data concerning the duration of immunity, the infectious period, the percentage of infected individuals taking COVID-19 tests, and the transmission rate. Since the whole world is currently still experiencing the pandemic, there will be much more research to come, so it can be expected that a lot of new facts and data becomes available in the future to improve the research. Additionally, even though data is missing, it must be pointed out that the Netherlands documents and publishes much and relatively well-kept open data, which benefits the research. This is in accordance with the research of Weerd et al. (2011), who advised the government to publish all the available information during a pandemic, to retain and gain the trust of the public.

8.2 CONCLUSIVE REMARKS

The model of this thesis contributes to a better understanding of risk perception and coping appraisal of the Dutch government during the COVID-19 pandemic. Forasmuch as the virus is relatively new, just like the COVID-19 literature itself, research about risk perception and coping appraisal together with the spatial diffusion of the virus is limited. In any case, research on pandemics (or epidemics) with a geographical component focusing on risk perception and coping appraisal seems to be scarce and underestimated. Even though the model did not possess all initially planned functionalities, a lot of information can be derived on the impact of different measures from the outcomes. There is much potential in future research about risk perception and coping appraisal with a geographical component, as is demonstrated by this research.

As COVID-19 is a relatively new virus, with still many unknown aspects, much future research is necessary, especially in terms of the risk perception, coping appraisal and their influence on the spatial diffusion of COVID-19. This research contributes to the first steps in obtaining a more complete understanding of the geographical component of governmental risk perception and coping appraisal during a pandemic.

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11. APPENDICES

Appendix A

ID's of the population, based on the age, commuting, household and Susceptible-Exposed-Infectious-Removed (SEIR). The data is acquired from Tjalma (2016) and used in the Netlogo COVID-19 model.

Nr	Age	Commuter	Household	SEIR	Unique ID	Unique ID Netlogo
1	0-5 yrs	Non	Yes	S	1.1.2.1	S1121
2	0-5 yrs	Non	Yes	E	1.1.2.2	E1122
3	0-5 yrs	Non	Yes	I	1.1.2.3	I1123
4	0-5 yrs	Non	Yes	R	1.1.2.4	R1124
5	5-12 yrs	Non	Yes	S	2.1.2.1	S2121
6	5-12 yrs	Non	Yes	E	2.1.2.2	E2122
7	5-12 yrs	Non	Yes	I	2.1.2.3	I2123
8	5-12 yrs	Non	Yes	R	2.1.2.4	R2124
9	12-17 yrs	School	Yes	S	3.2.2.1	S3221
10	12-17 yrs	School	Yes	E	3.2.2.2	E3222
11	12-17 yrs	School	Yes	I	3.2.2.3	I3223
12	12-17 yrs	School	Yes	R	3.2.2.4	R3224
13	12-17 yrs	Non	Yes	S	3.1.2.1	S3121
14	12-17 yrs	Non	Yes	E	3.1.2.2	E3122
15	12-17 yrs	Non	Yes	I	3.1.2.3	I3123
16	12-17 yrs	Non	Yes	R	3.1.2.4	R3124
17	17-25 yrs	Non	No	S	4.1.1.1	S4111
18	17-25 yrs	Non	No	E	4.1.1.2	E4112
19	17-25 yrs	Non	No	I	4.1.1.3	I4113
20	17-25 yrs	Non	No	R	4.1.1.4	R4114
21	25-35 yrs	Job	Yes	S	5.2.2.1	S5221
22	25-35 yrs	Job	Yes	E	5.2.2.2	E5222
23	25-35 yrs	Job	Yes	I	5.2.2.3	I5223
24	25-35 yrs	Job	Yes	R	5.2.2.4	R5224
25	25-35 yrs	Job	No	S	5.2.1.1	S5211
26	25-35 yrs	Job	No	E	5.2.1.2	E5212
27	25-35 yrs	Job	No	I	5.2.1.3	I5213
28	25-35 yrs	Job	No	R	5.2.1.4	R5214
29	25-35 yrs	Non	Yes	S	5.1.2.1	S5121
30	25-35 yrs	Non	Yes	E	5.1.2.2	E5122
31	25-35 yrs	Non	Yes	I	5.1.2.3	I5123
32	25-35 yrs	Non	Yes	R	5.1.2.4	R5124
33	25-35 yrs	Non	No	S	5.1.1.1	S5111
34	25-35 yrs	Non	No	E	5.1.1.2	E5112
35	25-35 yrs	Non	No	I	5.1.1.3	I5113
36	25-35 yrs	Non	No	R	5.1.1.4	R5114
37	35-50 yrs	Job	Yes	S	6.2.2.1	S6221
38	35-50 yrs	Job	Yes	E	6.2.2.2	E6222

39	35-50 yrs	Job	Yes	I	6.2.2.3	I6223
40	35-50 yrs	Job	Yes	R	6.2.2.4	R6224
41	35-50 yrs	Job	No	S	6.2.1.1	S6211
42	35-50 yrs	Job	No	E	6.2.1.2	E6212
43	35-50 yrs	Job	No	I	6.2.1.3	I6213
44	35-50 yrs	Job	No	R	6.2.1.4	R6214
45	35-50 yrs	Non	Yes	S	6.1.2.1	S6121
46	35-50 yrs	Non	Yes	E	6.1.2.2	E6122
47	35-50 yrs	Non	Yes	I	6.1.2.3	I6123
48	35-50 yrs	Non	Yes	R	6.1.2.4	R6124
49	35-50 yrs	Non	No	S	6.1.1.1	S6111
50	35-50 yrs	Non	No	E	6.1.1.2	E6112
51	35-50 yrs	Non	No	I	6.1.1.3	I6113
52	35-50 yrs	Non	No	R	6.1.1.4	R6114
53	50-65 yrs	Job	Yes	S	7.2.2.1	S7221
54	50-65 yrs	Job	Yes	E	7.2.2.2	E7222
55	50-65 yrs	Job	Yes	I	7.2.2.3	I7223
56	50-65 yrs	Job	Yes	R	7.2.2.4	R7224
57	50-65 yrs	Job	No	S	7.2.1.1	S7211
58	50-65 yrs	Job	No	E	7.2.1.2	E7212
59	50-65 yrs	Job	No	I	7.2.1.3	I7213
60	50-65 yrs	Job	No	R	7.2.1.4	R7214
61	50-65 yrs	Non	Yes	S	7.1.2.1	S7121
62	50-65 yrs	Non	Yes	E	7.1.2.2	E7122
63	50-65 yrs	Non	Yes	I	7.1.2.3	I7123
64	50-65 yrs	Non	Yes	R	7.1.2.4	R7124
65	50-65 yrs	Non	No	S	7.1.1.1	S7111
66	50-65 yrs	Non	No	E	7.1.1.2	E7112
67	50-65 yrs	Non	No	I	7.1.1.3	I7113
68	50-65 yrs	Non	No	R	7.1.1.4	R7114
69	65-80 yrs	Non	No	S	8.1.1.1	S8111
70	65-80 yrs	Non	No	E	8.1.1.2	E8112
71	65-80 yrs	Non	No	I	8.1.1.3	I8113
72	65-80 yrs	Non	No	R	8.1.1.4	R8114
73	80+ yrs	Non	No	S	9.1.1.1	S9111
74	80+ yrs	Non	No	E	9.1.1.2	E9112
75	80+ yrs	Non	No	I	9.1.1.3	I9113
76	80+ yrs	Non	No	R	9.1.1.4	R9114

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Appendix B-1

This data is deduced from Translink (2021) and is based on the check-ins with anonymous, personal and business public transport cards (OV-chipkaart) each day. The Tuesdays throughout 2020 are used to calculate travelling on a workday between 6 to 9 o'clock and 16 to 19 o'clock, which are the peak hours. *Reference work* is job commuting in the same month the year beforehand. *Total work* is job commuting each week (starting from week 11) in 2020. The last column, *Percentage commuting*, shows the percentage of job commuters that are travelling in 2020 compared to the reference month the year beforehand (*Percentage commuting = Total work / Reference work * 100)*.

Week	Date Tuesday	Reference Work (x1 000)	Total Work (x1 000)	Percentage Commuting 2020
11	10-3-2020	2363	2374	100,5
12	17-3-2020	2363	418	17,7
13	24-3-2020	2363	249	10,5
14	31-3-2020	2363	239	10,1
15	7-4-2020	2143	239	11,2
16	14-4-2020	2086	256	12,3
17	21-4-2020	2086	264	12,7
18	28-4-2020	2086	284	13,6
19	5-5-2020	2216	145	6,5
20	12-5-2020	2216	359	16,2
21	19-5-2020	2216	390	17,6
22	26-5-2020	2216	424	19,1
23	2-6-2020	1823	470	25,8
24	9-6-2020	1823	526	28,9
25	16-6-2020	1823	559	30,7
26	23-6-2020	1823	588	32,3
27	30-6-2020	1823	651	35,7
28	7-7-2020	1498	667	44,5
29	14-7-2020	1498	735	49,1
30	21-7-2020	1498	573	38,3
31	28-7-2020	1498	560	37,4
32	4-8-2020	1259	555	44,1
33	11-8-2020	1259	521	41,4
34	18-8-2020	1259	651	51,7
35	25-8-2020	1259	793	63,0
36	1-9-2020	2376	1011	42,6
37	8-9-2020	2376	1079	45,4
38	15-9-2020	2376	1055	44,4
39	22-9-2020	2376	1066	44,9
40	29-9-2020	2376	1015	42,7
41	6-10-2020	2383	986	41,4
42	13-10-2020	2383	773	32,4
43	20-10-2020	2383	694	29,1
44	27-10-2020	2383	887	37,2
45	3-11-2020	2510	974	38,8
46	10-11-2020	2510	866	34,5

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47	17-11-2020	2510	915	36,5
48	24-11-2020	2510	938	37,4
49	1-12-2020	1975	1007	51,0
50	8-12-2020	1975	965	48,9
51	15-12-2020	1975	755	38,2
52	22-12-2020	1975	455	23,0
53	29-12-2020	1975	378	19,1

Appendix B-2

This data is deduced from Translink (2021) and is based on the check-ins with anonymous, personal and business public transport cards (OV-chipkaart) each week. The weekends and the weekdays outside the rush hours throughout 2020 are used to calculate travelling. *Reference travelling* is the travelling in the same month the year beforehand. *Total travelling* is travelling each week (starting from week 11) in 2020. The last column, *Percentage travelling*, shows the percentage of GAET and VT that is travelling in 2020 compared to the reference month the year beforehand (*Percentage travelling = Total travelling / Reference travelling * 100)*. Note that in Appendix B-1 the job commuting is calculated for only one day a week (Tuesday) during the rush hours, while in Appendix B-2 we calculate it for the whole week outside the rush hours (including the weekends).

Week	Reference Travelling (x1 000 000)	Total Travelling (x1 000 000)	Percentage Travelling
11	15,92	13,81	86,8
12	15,92	6,16	38,7
13	15,91	5,05	31,7
14	15,83	4,95	31,3
15	15,30	5,08	33,2
16	15,58	4,99	32,0
17	15,58	5,16	33,1
18	15,67	5,11	32,6
19	15,10	4,52	29,9
20	15,10	5,34	35,4
21	15,10	5,45	36,1
22	15,10	5,75	38,1
23	15,57	5,87	37,7
24	15,55	5,95	38,2
25	15,55	6,16	39,6
26	15,55	6,60	42,4
27	15,42	6,45	41,8
28	15,85	6,54	41,2
29	15,85	6,70	42,3
30	15,85	5,71	36,0
31	15,85	5,69	35,9
32	12,95	5,78	44,7
33	12,95	5,31	41,1
34	12,95	6,21	48,0
35	12,95	6,98	53,9
36	5,81	8,26	142,1

37	6,32	8,36	132,2
38	6,32	8,47	134,0
39	6,32	8,24	130,4
40	6,32	8,36	132,3
41	16,39	8,43	51,4
42	16,39	7,72	47,1
43	16,39	7,21	44,0
44	16,39	8,25	50,3
45	17,00	8,87	52,2
46	17,04	8,09	47,4
47	17,04	8,01	47,0
48	17,04	8,23	48,3
49	15,62	8,05	51,6
50	15,53	8,37	53,9
51	15,53	7,65	49,3
52	15,53	6,49	41,8

Appendix C

Reisgedrag voor en tijdens de COVID-19 uitbraak

1. Wat is uw geslacht?
   - ☐ Man
   - ☐ Vrouw
   - ☐ Niet gespecificeerd
   - ☐ Zeg ik liever niet

2. Wat is uw leeftijd?

3. In welke gemeente woont u?

4. Uit hoeveel personen bestaat uw huishouden? Huishouden: de personen waarmee u samenwoont op hetzelfde adres.

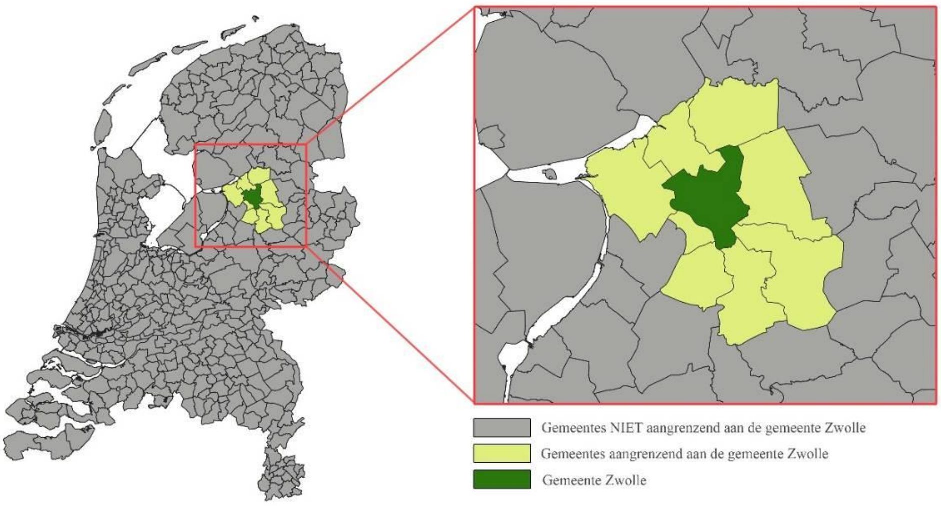
5. Als u op vorige vraag 2 of hoger heeft geantwoord: Wat zijn de leeftijden van de andere personen in uw huishouden? Mocht u de leeftijden niet weten dan is een schatting voldoende.

Reizen naar familie en vrienden voor de COVID-19 uitbraak

In de vragenlijst spreken we over uw eigen gemeente, aangrenzende gemeentes en niet-aangrenzende gemeentes. Op elke pagina is de beschrijving van de gemeentes terug te vinden.

Beschrijving gemeentes:
- Eigen gemeente: De gemeente waar u woont.
- Aangrenzende gemeentes: Zijn gemeentes die een grens delen met de gemeente waar uw woont. Uw eigen gemeente rekent u hier niet bij.
- Niet-aangrenzende gemeentes: Delen geen grens en zijn dus alle overige gemeentes naast uw eigen gemeente en de aangrenzende gemeentes.

Hieronder is een voorbeeld te zien van de gemeente Zwolle.



Voorbeeld: In het geval dat Zwolle de gemeente is waar u woont

6. Hoe veel keer ging u gemiddeld per maand op bezoek bij familie of vrienden thuis in uw EIGEN gemeente VOOR de eerste Corona uitbraak? Een ruwe schatting van het aantal bezoeken is voldoende.

7. Hoe veel keer ging u gemiddeld per maand op bezoek bij familie of vrienden thuis in een AANGRENZENDE gemeente VOOR de eerste Corona uitbraak? Een ruwe schatting van het aantal bezoeken is voldoende.

8. Hoe veel keer ging u gemiddeld per maand op bezoek bij familie of vrienden thuis in een gemeente NIET AANGRENZEND aan uw eigen gemeente VOOR de eerste Corona uitbraak? Een ruwe schatting van het aantal is voldoende.

Reizen naar familie en vrienden tijdens de eerste COVID-19 lockdown

9. Hoe veel keer ging u gemiddeld per maand op bezoek bij familie of vrienden thuis in uw EIGEN gemeente TIJDENS de eerste lockdown? Een ruwe schatting van het aantal bezoeken is voldoende.

10. Hoe veel keer ging u gemiddeld per maand op bezoek bij familie of vrienden thuis in een AANGRENZENDE gemeente TIJDENS de eerste lockdown? Een ruwe schatting van het aantal bezoeken is voldoende.

11. Hoe veel keer ging u gemiddeld per maand op bezoek bij familie of vrienden thuis in een gemeente NIET AANGRENZEND aan uw eigen gemeente TIJDENS de eerste lockdown? Een ruwe schatting van het aantal bezoeken is voldoende.

12. Wat zijn de bepalende factoren voor uw keuze om wel of niet te reizen naar familie en vrienden tijdens een lockdown? Geef een korte toelichting.

13. Hoeveel risico denkt u dat u loopt door te reizen naar familie of vrienden tijdens een lockdown? Geef een korte toelichting.

14. Verschilde uw reisgedrag in de tweede lockdown van uw reisgedrag in de eerste lockdown? Geef een korte toelichting.

15. Heeft u een kind jonger dan 12 jaar?
    - ☐ Ja [ga door naar vraag 16]
    - ☐ Nee [ga door naar einde enquête]

Reisgedrag kind voor en tijdens de COVID-19 uitbraak

Mocht u meerdere kinderen hebben, vul dit gedeelte van het formulier voor één van hen in.

16. Hoe oud is uw kind?

Voor de eerste Corona uitbraak

17. Hoe veel keer ging uw kind gemiddeld per maand op bezoek bij familie of vrienden thuis in uw EIGEN gemeente VOOR de eerste Corona uitbraak? Een ruwe schatting van het aantal bezoeken is voldoende.

18. Hoe veel keer ging uw kind gemiddeld per maand op bezoek bij familie of vrienden thuis in een AANGRENZENDE gemeente VOOR de eerste Corona uitbraak? Een ruwe schatting van het aantal bezoeken is voldoende.

19. Hoe veel keer ging uw kind gemiddeld per maand op bezoek bij familie of vrienden thuis in een gemeente NIET AANGRENZEND aan uw eigen gemeente VOOR de eerste Corona uitbraak? Een ruwe schatting van het aantal bezoeken is voldoende.

Eerste lockdown

20. Hoe veel keer ging uw kind gemiddeld per maand op bezoek bij familie of vrienden thuis in uw EIGEN gemeente TIJDENS de lockdown? Een ruwe schatting van het aantal bezoeken is voldoende.

21. Hoe veel keer ging uw kind gemiddeld per maand op bezoek bij familie of vrienden thuis in uw EIGEN gemeente TIJDENS de lockdown? Een ruwe schatting van het aantal bezoeken is voldoende.

22. Hoe veel keer ging uw kind gemiddeld per maand op bezoek bij familie of vrienden thuis in een gemeente NIET AANGRENZEND aan uw eigen gemeente TIJDENS de lockdown? Een ruwe schatting van het aantal bezoeken is voldoende.

Einde enquête

Heeft u verder opmerkingen, aanmerkingen observaties, en / of ervaringen met betrekking tot (veranderingen in) reisgedrag voor en tijdens de Coronatijd?

Bedankt voor het invullen van deze enquête!

Appendix D

The reduction in travelling as simulated by the Netlogo model for the predefined lockdowns, the Roadmap scenario, the economic scenario and the age scenario. If the commuting or travelling is 0.0% there is no reduction in commuting or travelling. If it is -100.0% it means no commuter or traveller participates in that kind of commuting or travelling. All percentages relate to the initial pre-lockdown numbers, i.e. when no measures are implemented. The lower the percentage, the lower the participation in commuting and travelling, in other words, the higher the reduction of commuters and travellers. The reduction in travelling is calculated for each month and does not depend on the month beforehand, i.e. the percentage does not show a reduction with regard to the month beforehand, but stands on its own. These tables can help the reader to gain more insight into the effect of different measures' implementation (coping appraisal) for the predefined lockdowns and the three scenarios on the commuting and travelling behaviour.

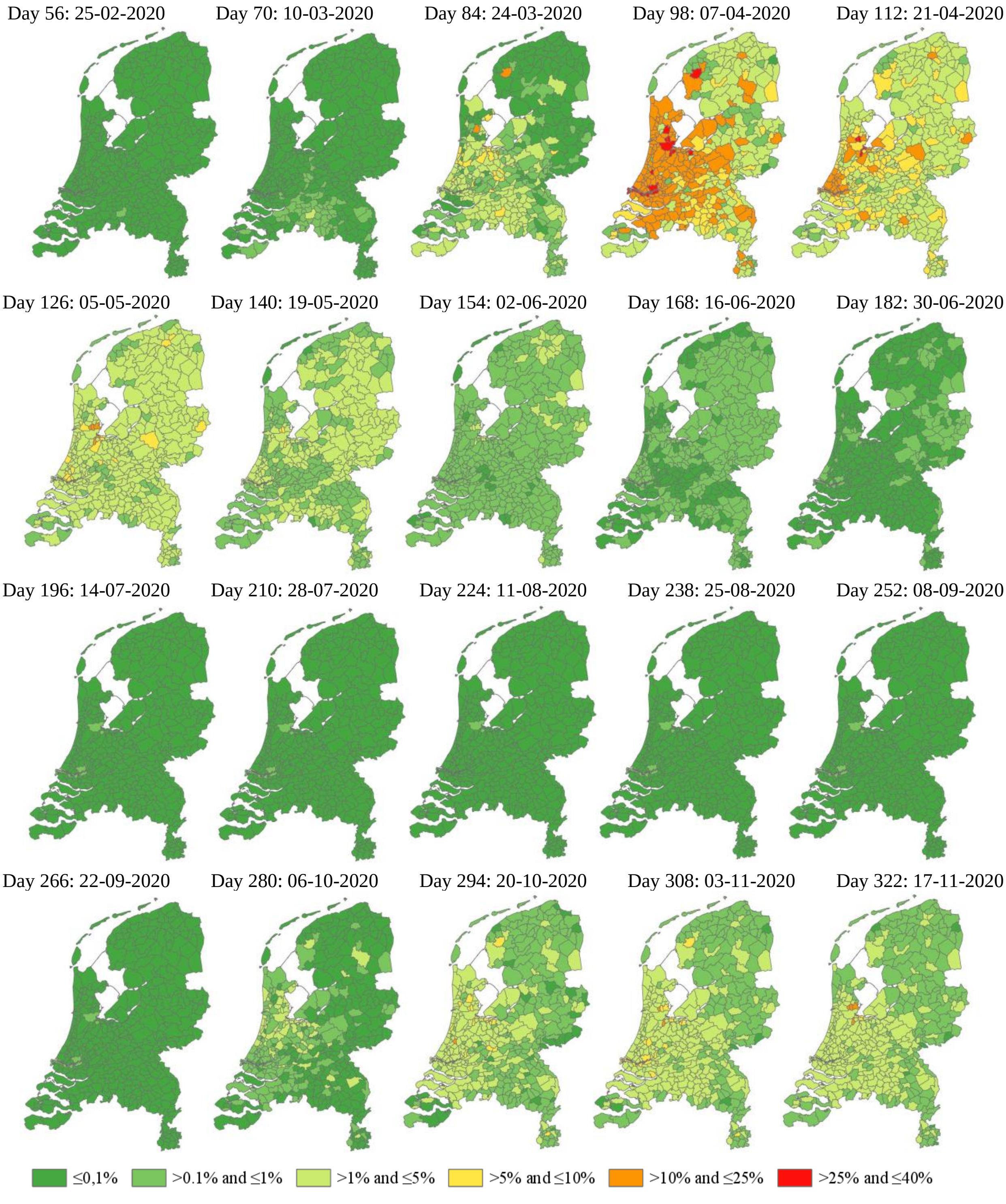
	Predefined lockdown				**Roadmap scenario**			
	Job commuting	***School commuting***	***GAET***	***VT***	***Job commuting***	***School commuting***	***GAET***	***VT***
March	-16.5%	-19.4%	-3.9%	-15.5%	-27.8%	-13.5%	-6.6%	-15.5%
April	-85.0%	-100.0%	-20.0%	-80.0%	-67.9%	-82.9%	-17.0%	-80.0%
May	-85.0%	-100.0%	-20.0%	-80.0%	-5.0%	-4.9%	-1.2%	-80.0%
June	-85.0%	-100.0%	-20.0%	-80.0%	0.0%	0.0%	0.0%	-80.0%
July	-85.0%	-3.2%	-20.0%	-2.6%	0.0%	0.0%	0.0%	-2.6%
August	-2.7%	0.0%	-0.6%	0.0%	0.0%	0.0%	0.0%	0.0%
September	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
October	0.0%	0.0%	0.0%	0.0%	-51.6%	-31.7%	-12.9%	0.0%
November	0.0%	0.0%	0.0%	0.0%	-42.9%	-31.5%	-10.7%	0.0%
December	-49.7%	-71.0%	-14.2%	-49.7%	-3.6%	-3.2%	-0.3%	-49.7%

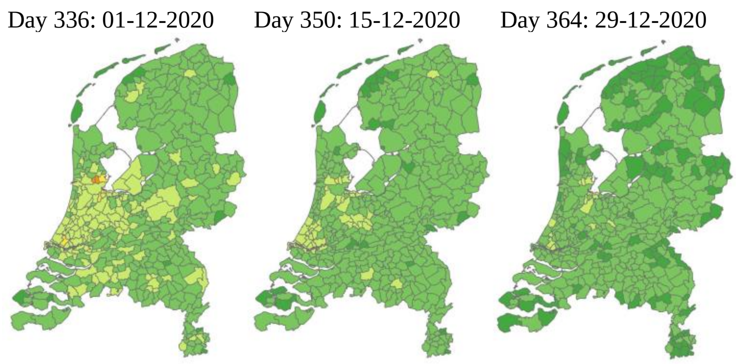
	Economic scenario				**Age scenario**			
	Job commuting	***School commuting***	***GAET***	***VT***	***Job commuting***	***School commuting***	***GAET***	***VT***
March	-23.7%	-18.1%	-9.1%	-28.1%	-21.0%	0.0%	-5.3%	-18.3%
April	-63.5%	-77.7%	-16.0%	-63.5%	-71.6%	-0.1%	-18.5%	-75.5%
May	-0.2%	0.0%	-0.2%	-0.4%	-20.8%	-7.9%	-5.2%	-53.9%
June	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-15.1%
July	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
August	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
September	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
October	-54.2%	-35.7%	-16.8%	-55.2%	-44.5%	0.0%	-11.1%	-44.0%
November	-39.4%	-29.1%	-11.6%	-39.4%	-37.2%	0.0%	-10.0%	-37.5%
December	0.0%	0.0%	-0.6%	-1.3%	-5.6%	0.0%	-1.4%	-20.0%

Appendix E-1

Running Netlogo COVID-19 model without lockdowns or other measures in the Netherlands in 2020. The legend is visible at the bottom of the page and is the same for all maps in this thesis. The colours represent the percentage of infected individuals per municipality.

No lockdowns: the percentage of infected individuals per municipality in the Netherlands (2020)

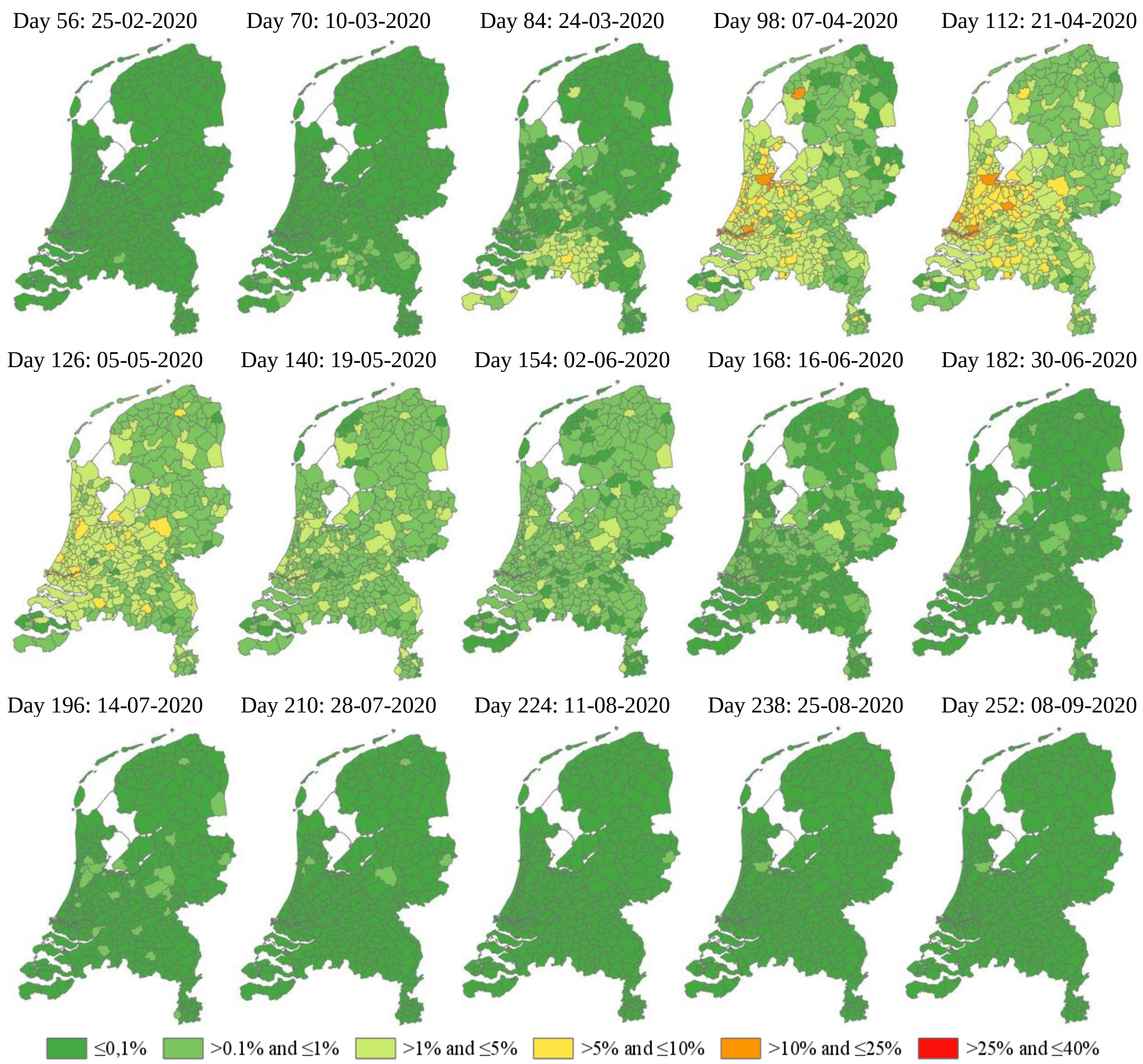


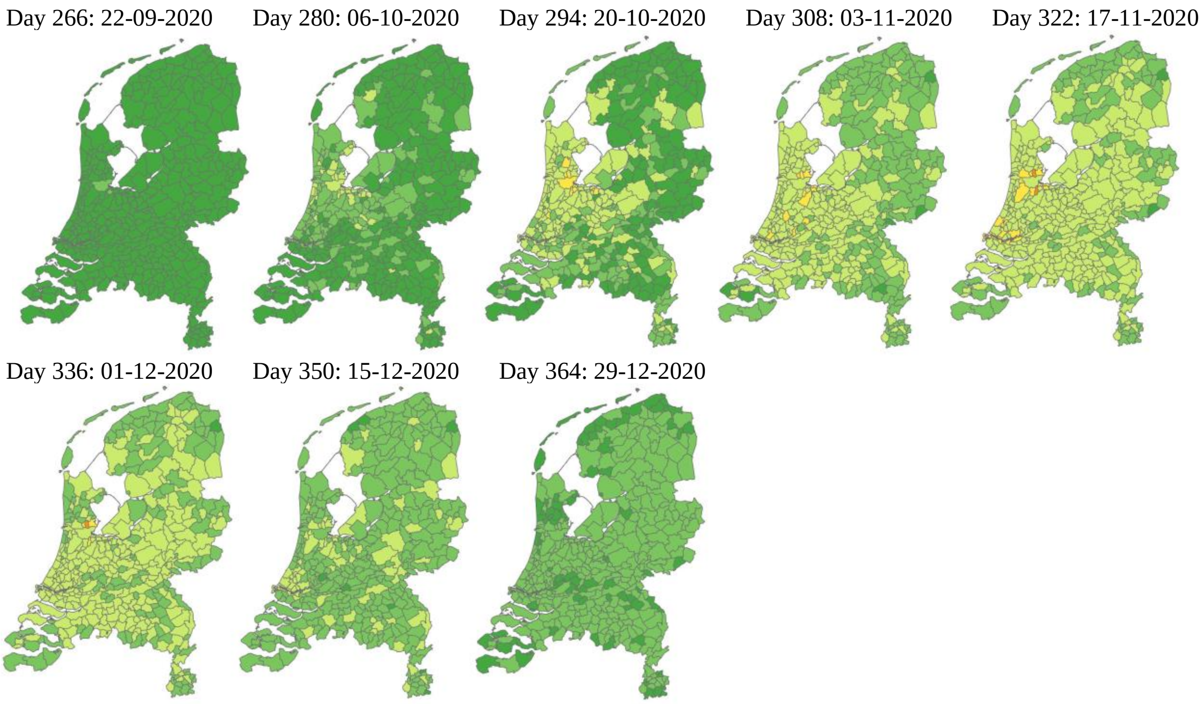


Appendix E-2

Running Netlogo COVID-19 model with predefined lockdowns in the Netherlands in 2020. The legend is visible at the bottom of the page and is the same for all maps in this thesis. The colours represent the percentage of infected individuals per municipality.

Predefined lockdowns: the percentage of infected individuals per municipality in the Netherlands (2020)

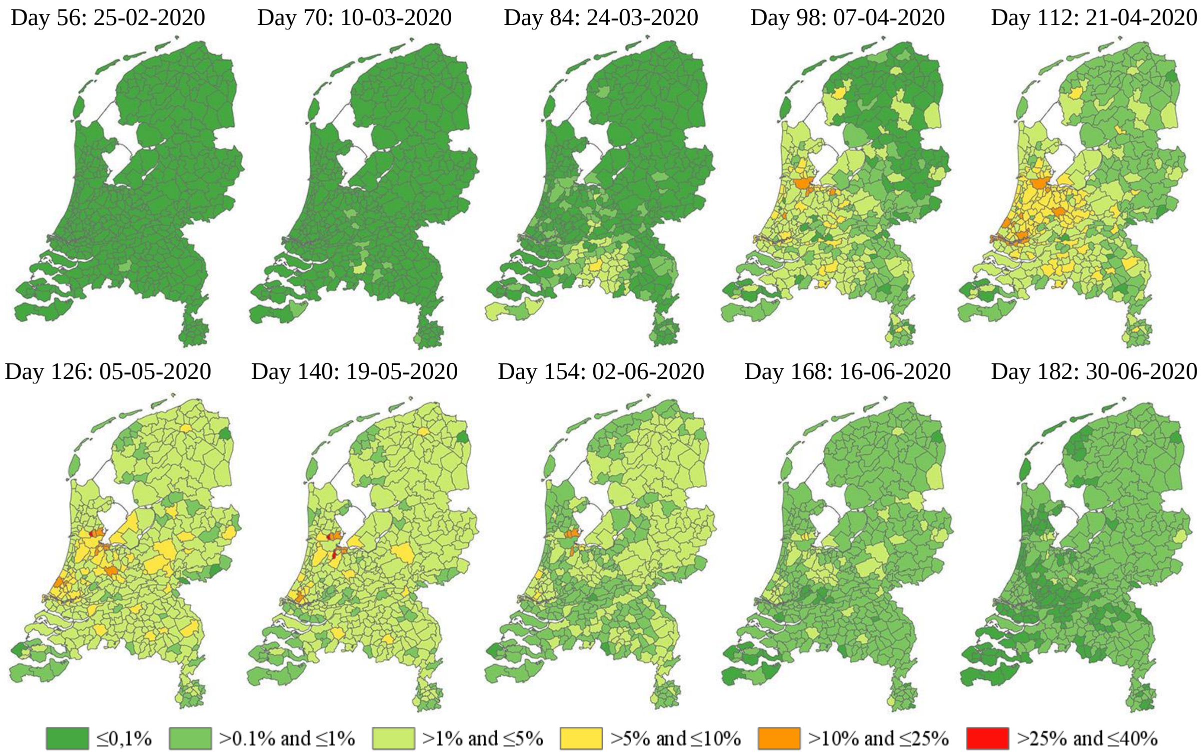


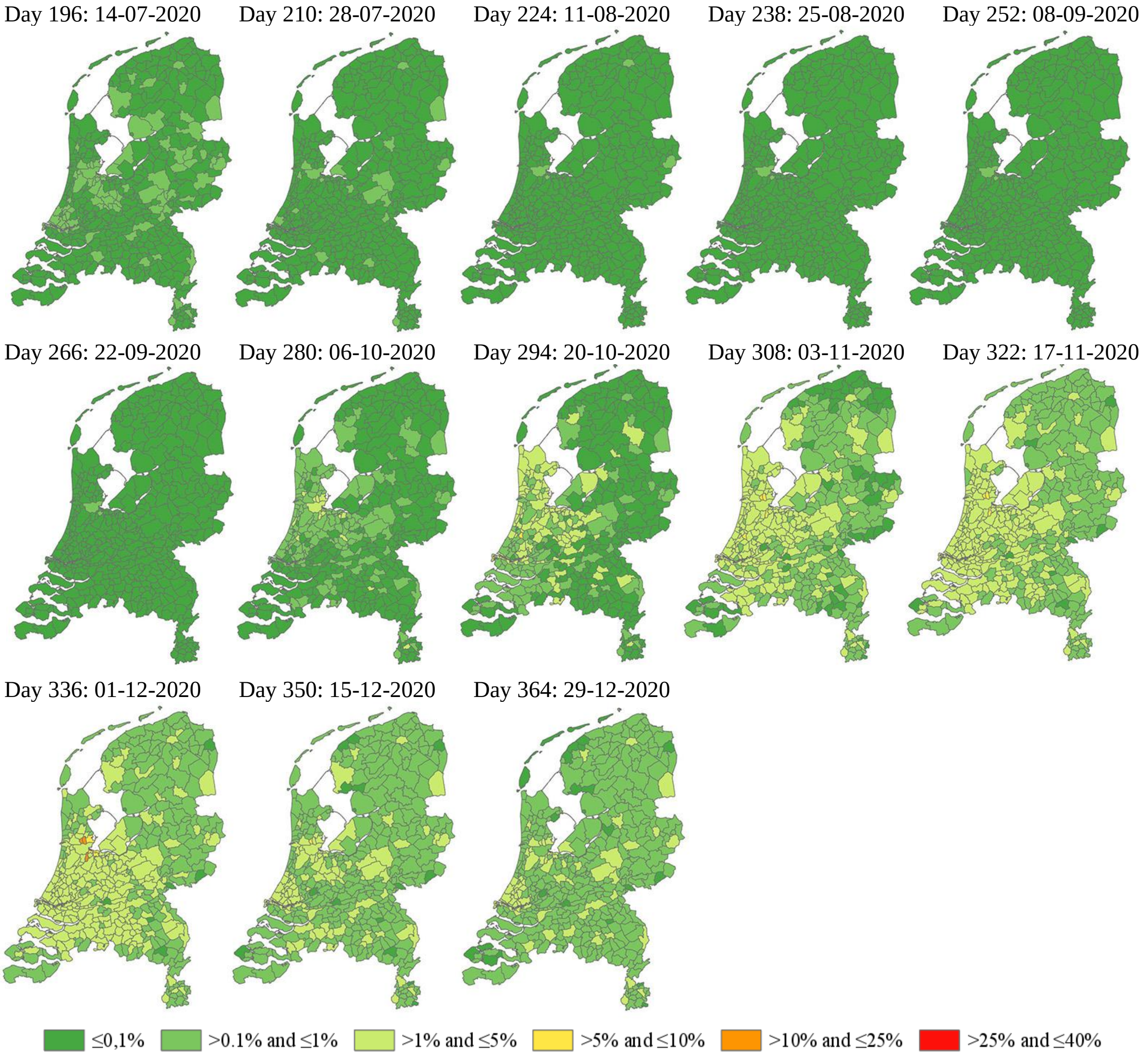


Appendix E-3

Running Netlogo COVID-19 model with the Roadmap scenario. The other two scenarios (economic and age) have almost identical outcomes. The legend is visible at the bottom of the page and is the same for all maps in this thesis. The colours represent the percentage of infected individuals per municipality.

Road map scenario: the percentage of infected individuals per municipality in the Netherlands (2020)




Day 196: 14-07-2020
Day 210: 28-07-2020
Day 224: 11-08-2020
Day 238: 25-08-2020
Day 252: 08-09-2020
Day 266: 22-09-2020
Day 280: 06-10-2020
Day 294: 20-10-2020
Day 308: 03-11-2020
Day 322: 17-11-2020
Day 336: 01-12-2020
Day 350: 15-12-2020
Day 364: 29-12-2020
≤0,1%
>0.1% and ≤1%
>1% and ≤5%
>5% and ≤10%
>10% and ≤25%
>25% and ≤40%