DEMAND AND SUPPLY PLANNING FOR COVID-19 VACCINE IN TURKEY WITH AN ANTI-VACCINE SURVEY

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DEMAND AND SUPPLY PLANNING FOR COVID-19 VACCINE IN TURKEY WITH AN ANTI-VACCINE SURVEY

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ABSTRACT

The Covid-19 virus, which affects many people, continues in a very contagious state. Vaccination is necessary to end this pandemic period, which everyone wants to end as soon as possible. The studies in the literature focuses on different phases of the vaccination such as product, production, allocation or distribution. Existing, expected and sudden outbreaks are studied considering developed and developing countries. But many studies focus on expected outbreaks in developed countries. There are, however, a limited number of studies for sudden outbreaks because of the uncertainties. Therefore, in this study, we focus on Covid-19, which is a sudden outbreak, and the study is executed in a developing country, Turkey. As the attitude towards vaccination might differ across subpopulations, vaccine hesitancy might affect all of purchasing, distribution, and allocation decisions of vaccines. We conduct a survey in order to reduce the uncertainties about the vaccine demand. We analyze on vaccine selections, government decisions about the purchase of the vaccines, vaccination groups and create a supply chain plan.

Covid-19 affects us in a very harmful way and there are several issues we can consider in order to come up with an efficient vaccination plan. Since the vaccine demand is the key factor that affects our decisions, we have to forecast the demand with the least error we can get. If the predicted demand is higher than the actual demand, we would purchase vaccines more than we need and we have to deal with wastage and purchasing costs. If the predicted demand is less than the actual demand, we would miss the opportunity to vaccinate more people and get closer to the end of the pandemic. Thus, by predicting the demand in an accurate way, we can make more meaningful decisions in our supply chain. In our survey, we try to understand the thoughts of individuals in Turkey by asking questions about side effects of vaccines, the acceptance of vaccines, the distrust

of the number of cases and deaths announced. The responses help us predict the vaccine demand. After forecasting the weekly demand, we use them in our optimization model to construct a weekly vaccine supply plan for Turkey over a one-year planning horizon. The goal of the optimization model is to minimize the total costs of purchasing, transportation, storage, backordering and to reach the herd immunity. In this model, we consider storage and transportation capacity limits, minimum required vaccination rate to reach the herd immunity, and vaccine demand satisfaction with respect to priorities of the cities.

ÖZETÇE

Birçok insanı etkisi altına alan Covid-19 virüsü oldukça bulaşıcı bir halde devam ediyor. Herkesin bir an önce bitmesini istediği bu pandemi dönemini bitirmek için aşılanma şart. Literatürdeki çalışmalar aşının ürün, üretim, tahsis veya dağıtım gibi farklı aşamalarına odaklanmaktadır. Mevcut, beklenen ve ani salgınlar gelişmiş ve gelişmekte olan ülkeler dikkate alınarak incelenmiştir. Ancak birçok çalışma gelişmiş ülkelerdeki beklenen salgınlara odaklanıyor. Belirsizlikler nedeniyle ani salgınlar için sınırlı sayıda çalışma bulunmaktadır. Bu nedenle, bu çalışmada ani bir salgın olan Covid-19'a odaklanıldı ve çalışma gelişmekte olan bir ülke olan Türkiye'de yürütüldü. Aşıya karşı tutum popülasyonlar arasında farklılık gösterebileceğinden, aşı tereddütü aşıların tüm satın alma, dağıtım ve tahsis kararlarını etkileyebilir. Aşı talebiyle ilgili belirsizlikleri azaltmak için bir anket yapıyoruz. Aşı seçimlerini, aşıların satın alınmasıyla ilgili hükümet kararlarını, aşı gruplarını analiz ediyor ve bir tedarik zinciri planı oluşturuyoruz.

Covid-19 bizi çok zararlı bir şekilde etkiliyor ve etkili bir aşı planı oluşturabilmek için göz önünde bulundurmamız gereken birkaç konu var. Aşı talebi, kararlarımızı etkileyen en önemli faktör olduğundan, talebi en az hata ile tahmin etmemiz gerekiyor. Öngörülen talep, gerçek talepten daha yüksek olursa, ihtiyacımızdan daha fazla aşı satın alırız. İsraf ve satın alma maliyetleri ile uğraşmak zorunda kalırız. Öngörülen talep, gerçek talepten daha az olursa, daha fazla insanı aşılama ve pandeminin sonuna yaklaşma fırsatını kaçırmış oluruz. Böylece talebi doğru bir şekilde tahmin ederek tedarik zincirimizde daha anlamlı kararlar verebiliriz. Anketimizde aşıların yan etkileri, aşıların kabulü, açıklanan vaka ve ölüm sayılarına güvensizlik gibi konularda sorular sorarak Türkiye'deki bireylerin düşüncelerini anlamaya çalışıyoruz. Verilen yanıtlar aşı talebini tahmin etmemizde bize yardımcı oluyor. Haftalık talebi tahmin ettikten sonra bunu, bir yıllık planlama ufku

boyunca, Türkiye'de haftalık aşı tedarik planı oluşturmak için optimizasyon modelimizde kullanıyoruz. Optimizasyon modelinin amacı, satın alma, nakliye, depolama, geri sipariş toplam maliyetlerini en aza indirmek ve sürü bağışıklığına ulaşmaktır. Bu modelde, depolama ve taşıma kapasitesi limitlerini, sürü bağışıklığına ulaşmak için gereken minimum aşılama oranını ve farklı önceliklere sahip illerin aşı talep memnuniyetlerini dikkate alıyoruz.

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I would like to thank my advisor, Zehra Melis Teksan, for her great contributions to me and my thesis at Özyeğin University. She always kept in touch with me and gave me different perspectives. We discussed everything I did with her and decided everything together.

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CHAPTER I

INTRODUCTION

At the end of 2019, we met a virus called "SARS-CoV-2". Then, on March 11, 2020, when the first case was seen in Turkey, a pandemic was declared by the World Health Organization (WHO). It is very unlikely that a virus that can spread so easily will disappear on its own. Therefore, governments, profit-, and non-profit organizations, as well as individuals have to take some actions to end it. Dasaklis et al. [3] declare that there are three types of actions in pandemics. First one is pharmaceutical interventions, where public health treatment programs (like vaccination campaigns) take place and the limited resources are utilized. These resources can be discrete (e.g. vaccines, antibiotics or antiretroviral drugs, etc.) or continuous (e.g. funds). The second one is non-pharmaceutical interventions, such as the closure of schools, voluntary quarantines over a wide area, social distancing and travel limitations. The last action is where both interventions are combined and harmonized control actions are proposed.

Given the fast contingency and the potential damages of Covid-19 virus, the use of both pharmaceutical and non-pharmaceutical intervations are required. Many non-pharmaceutical interventions were performed in Turkey. Schools closed immediately, rules about social distancing and the usage of masks are constantly being reminded by the government. Travel restrictions and quarantines have been tried repeatedly across the country. There were also times when restrictions were applied only in risky areas which had high number of cases or low vaccination rate. Despite all the actions and precautions taken, Covid-19 outbreak continues to be in its pandemic period because pharmaceutical interventions are also important. Especially, the ones that are given before we get infected by the virus.

The government informs the public about drugs and vaccines. Confusion continues about which drugs to use when a person is infected. The drugs used by the Covid-19 patients were changed several times. Doses of drugs were also discussed for a long time. For example, the drug called Favipiravir should have been taken 8 times in the morning and in the evening on the first day of illness. On the other 4 days, the drug should have been taken 3 times in the morning and in the evening. Some patients rejected the use of the drugs because they did not want to use such high doses of drugs. Later in practice, it is shown that this particular drug did not have a significant effect in the healing process; hence, labeled as ineffective and its usage is removed from the practice. In addition, some people did not want to use vaccines because of some rumors that vaccines will cause myocardium, heart attack, infertility etc. The supply for the drugs were not limited. When we analyze the supply of the vaccine, there were some limitations in supply. Since Turkey had not started to produce the domestic vaccine during the peak periods of the outbreak, the vaccines needed to be sourced from other countries as many other countries with no vaccine invention did. This created a great shortage globally in the supply of vaccines resulting in limited supply of doses and long lead times.

Experts say that in order to end the pandemic, it is required to achieve a 67% of vaccination rate to reach the herd immunity. This is the most important action required and it has not been achieved yet. The biggest reason is that we need to manage the supply chain in a better way. The vaccine brands, the number of doses, time between doses are needed to be determined by the health professionals. Meanwhile the supply chain and optimization experts should adopt the task of optimizing the demand and supply planning of vaccines under severely critical conditions and high uncertainty.

In sudden outbreaks, the demand for the vaccines is very unpredictable. In the first place, people are worried about the side effects of vaccines. In addition to that, some factors reduce the demand for the vaccine including different declarations of the protection of vaccine in different countries, the emergence of various mutations of the virus and some conspiracy theories. In the second place, the fact that vaccinations are compulsory for some events and venues and that some countries would apply vaccination passports are among the reasons that increase the demand. It is significantly challenging to estimate the effects of these factors to the vaccine demand. That's why we need to collect information to be able to see those effects. And this can be made by conducting a survey.

In a situation where there is a limited supply that needs to be properly distributed, purchasing vaccines more than the demand would cause financial problems and unused vaccines would go to waste. Purchasing vaccines less than we need would make us unable to vaccinate enough people. So, we need to analyze the people's opinions about vaccination to manage the vaccine supply chain in a better way.

In this study, we forecast the demand for the coronavirus vaccine and try to put forward a methodology to create an effective supply chain plan. In the literature review chapter, the studies on the vaccine supply chain will be explained. The methodology chapter is divided into demand forecasting and supply planning. In the demand forecasting section, we explain how we can forecast the demand for the coronavirus vaccine. In the supply planning section, a multi-objective optimization model that can be used for the vaccine supply chain plan is created. In the result section, numerical results are listed.

CHAPTER II

LITERATURE REVIEW

As Duijzer et al. [4] state, the literature contains articles about four main subjects of the vaccine supply chain. The first one is which vaccines to use. Most of these articles are about the influenza vaccine and catch-up schedules of pediatric diseases vaccines. Smalley et al. [5] provide a decision tool that constructs the best catch-up schedule given the vaccination history and the age of a child. For our case, the only thing we should consider is which vaccine brand should we use because the vaccines are not administered under the age of 18 in our country. Currently, three brands of vaccines are used in vaccinations in Turkey; Sinovac, Biontech and Turkovac.

The second subject that the articles in the literature work on is how many doses should be produced. Vaccine demand is most of the time uncertain, because being vaccinated is everyone's own choice. Ibuka et al. [6] create a game in which groups of 8-10 people spend a period with or without being vaccinated. Each participant is given 2000 initial points and lose them when buying the vaccine or when he get infected. They find that higher observed vaccination rate within the group during the previous round of the game decreases the likelihood of an individual's vaccination acceptance, indicating the existence of free-riding behavior. We should consider this in our paper as well.

Arifoglu et al. [7] also study the effect of individuals' behaviour on demand by introducing two concepts, positive externality and negative externality. Positive externality means self-interested individuals do not care about the social benefit of protecting others via reduced infectiousness. Negative externality means self-interested individuals ignore that vaccinating people with high infection costs is more beneficial for the society when supply is limited. Increasing the number of priority groups reduces the negative externality effect further by decreasing the inefficiency and uncertainty in the allocation mechanism.

In Turkey, there are 26 priority groups. Under these circumstances, there can be two scenarios. In the first one, the manufacturer decides how many vaccines to produce because of the yield uncertainty of the production process and the government decides who will get vaccinated. In the other one, the government decides the quantity according to infectiousness of the disease and the individuals decide whether to get vaccinated or not. As we need to consider the interests of both the government and the producers, we must do a balanced analysis to determine the right strategy.

The uncertainty about the demand causes yield uncertainties and the producers want to make profit. That makes the vaccine industry unattractive, especially for unexpected diseases. Deo Corbett et al. [8] state that if the market is not attractive enough, then any amount of yield uncertainty decreases the number of firms at equilibrium. However, if the market is attractive enough, then limited yield uncertainty can actually result in entry of more firms than the deterministic case. The reason could be that there is a little chance to make a lot of money in situations of uncertainty, so people become greedy.

For Covid-19 vaccine, the market is not attractive enough. De Treville et al. [9] assert that there is a probability of demand dropping to zero for all suppliers. So, the number of firms would be insufficient and there would be a decrease in the vaccine supply. In this situation, government can offer some incentives in order to increase attractiveness. Chick et al. [10] design a contract for buyer (governmental public health service) and supplier (vaccine manufacturer) that shares production yield risks, which are initially carried by the manufacturer, with the public payor by carefully balancing the price per dose of vaccine delivered with a small charge for production effort by the manufacturer.

To understand more about the coordination between the government and the producers, we need to consider that the government is a non-profit institution and wants to receive vaccines on time. On the other hand, the producers are for-profit organizations and want to start production when demand becomes more certain. Dai et al. [11] show that existing supply contracts fail in coordinating the supply chain in this respect. They suggest new contracts that coordinates the supply chain and allows for flexible profit division. In addition, Adida et al. [12] state that a spontaneous market behavior leads to a vaccine coverage that is often too low to achieve herd immunity and is always less than the socially optimal level of vaccine. So, decreasing the uncertainties should be our first aim.

Lydon et al. [1] try to understand the role of the private sector in immunization supply chain and logistics systems for developing countries. The authors conclude that outsourcing can be beneficial, although it is highly important to carefully determine which parts of the supply chain should be outsourced and to whom. Figure 1 shows a comparison of the government and private sector:

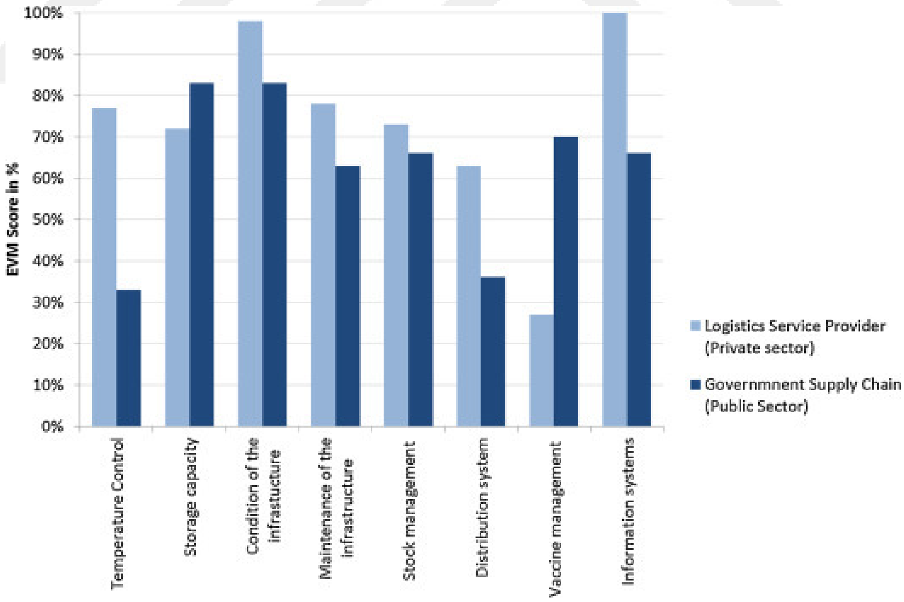

Figure 1: Comparison of the government and private sector [1]

Another subject that can be analysed is the allocation of the vaccines. Some studies divide the population into smaller groups and think that a proportional vaccination should be given. Some studies suggest that the regions that have less cases or less population should be vaccinated first because reaching the herd immunity can be easier in those regions. Some studies also consider network models, where a graph is used to represent regions (or individuals) and their connections. They investigate the optimal removal of nodes. When the network represents a population, node removal can be interpreted as either vaccination or quarantining.

The groups that can spread the disease easily should be prioritized as well. Most of the time these groups include children. Furthermore, the groups that have higher risks, especially elderly people should be prioritized. A priority list has been published by the government for Covid-19 vaccine in Turkey. The list is constructed by taking into account both age factor, occupations and the presence of chronic diseases.

In the health economics literature and the epidemiological literature, the studies focuse only on cost effectiveness. The aim is to decrease the total vaccination costs and the patient recovery costs by comparing different interventions and determining which ones are cost-effective with budget constraints. Dimitrov's paper [13] is one of those studies that tries to select the best intervention strategies for malaria in Nigeria. Three models are included in their study. Disease Risk Model (according to geographic region), Implementation Model (the costs of implementing intervention actions across the region) and Mortality and Economic Impact Model. With the help of these models, they determine the best actions and optimal locations for distribution centers under given budget constraints. Their aim is to minimize the active infectious and persistent latent individuals, as well as the cost associated with the implementation of the control strategies. Turkish government is using almost the same approach, they mostly focus on reducing active cases in order to reduce the burden on hospitals and intensive care services.

There are studies about the wastages as well. Pishvaee et al. [14] propose a method to design a sustainable medical supply chain, considering the complete life cycle of medical supplies and waste of medial needles and syringes. Saif et al. [15] model the cold supply chain design problem as a concave mixed-integer minimization problem with dual objectives of minimizing the total cost including capacity, transportation, inventory and the global warming impact. According to them, 25 percent reduction in the greenhouse gas emissions can be achieved with only 3 percent increase in cost. Assi et al. [16] state that there is a closed vial waste which occurs mostly because of errors in storage and transportation, like when vials get too warm or too cold. There is also an open vial waste which occurs mainly because of immunization workers' practices or unused doses from multi-dose vials are thrown away. We can understand how important storage, transportation and vaccination decisions are from this study.

Haidari [17] made a study about the importance of storage and transportation. Their objective is to determine whether adding cold storage devices or increasing transport frequency would have a greater impact and to identify the locations where these additions would be most beneficial, as measured by vaccine availability. The action that increases the vaccine availability the most is to triple the transport frequency. This is followed by doubling the transport frequency. The most ineffective method was to add storage.

The last but the most important subject we need to consider is the distribution of the vaccines. Designing the supply chain is very crucial in order to have a more efficient supply chain. Kaufmann et al. [18] assert that there are 2 segments; the segment that produces vaccines and moves them to the receiving countries, and the segment that distributes the vaccines within the receiving country. The first segment partly takes place in developed countries, whereas the second segment takes place in developing countries. Turkey is in the second segment. The authors recommend that coordination between the two segments of the vaccine supply chain should be improved by not only optimizing only one component of the supply chain, such as international transport, or one attribute, such as cost, but also considering the overall efficiency and effectiveness.

Zaffran et al. [19] underline the current issues of the vaccine supply chains: impact of vaccine schedules and presentations on cold chain volume requirements, choices for cold chain equipment, cold chain maintenance and temperature control, immunization-related information systems, human resources for the vaccine supply chain, vaccine cost and wastage, coping mechanisms. Since we use Biontech vaccines in Turkey, we need to consider the cold chain requirements. Besides, we do not have an information system, we only have a website that shows the number of people vaccinated with first, second and third doses. We also do not consider the wastage and the training of human resources. These three issues can be improved in our current system.

Alam et al. [20] try to investigate the major challenges in the COVID-19 vaccine supply chain, rank the challenges using the Intuitionistic Fuzzy DEMATEL method and identify the causal links among those challenges. The highest ranking challenge in the cause group is lack of vaccine monitoring bodies (C14). In contrast, the top ranked in the effect group is consumers' unwillingness to vaccinate (C4). This means we should improve our monitoring bodies and the consumers' behaviours are affected easily by the other ones.

Privett et al. [2] explain top 10 global supply chain challenges by defining them as item-level, facility-level and system-level. System level challenges which are lack of coordination, demand information, human resource dependency and shipment visibility are the root causes for all the challenges. Facility level challenges (inventory management, order management, shortage avoidance, warehouse management and shipment visibility) are affected by the previous challenges and effects the item level challenges. Expiration and temperature control are the item level challenges. Figure 2 shows the relation of these challenges:

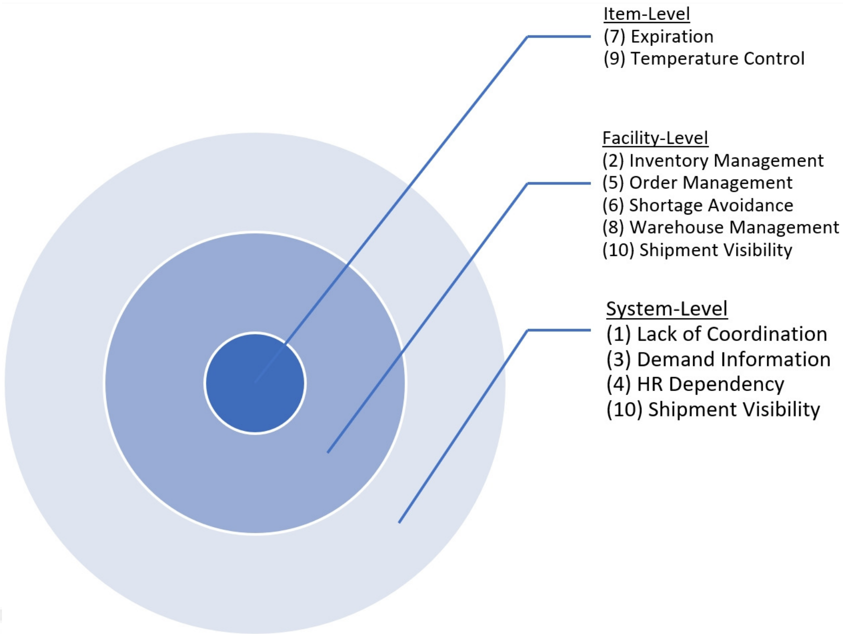

Figure 2: Privett's relation of challenges [2]

To sum up, there are many studies in the literature that focuses on which vaccine should we use, how many vaccines to produce and when, the change in people's behaviours according to the other people's behaviours, the uncertanties about the demand and the yield, how to allocate and distribute the vaccines, the key challenges in the vaccine supply chain etc. We can use these information to get an idea of the vaccine supply and create a methodology which can be used in a pandemic to create an efficient supply plan.

CHAPTER III

METHODOLOGY

In this thesis, our aim is to find the right amount of vaccines to procure weekly in order to match the supply with the demand. Not satisfying the demand for vaccines immediately is a general concern. However, under the capacity limitations of supply logistics of the vaccines, it is inevitable that some demand would be satisfied at a later time causing backorders, in case the demand for the vaccines are higher than the supply capacity in the beginning of the planning horizon. The priorities of the provinces and the herd immunization are other concerns in our vaccine supply chain. We include all in our optimization model. Using that model, we want to create a weekly vaccination supply plan for one year time horizon but before the model we need to know the weekly demand.

The demand for vaccination is not readily available, therefore we propose a method on how the demand for vaccines can be predicted. Eventually, our work has to consist of two phases. The first one is demand forecasting where we will try to understand people's opinions about getting vaccinated so that we can come up with a weekly demand forecast. The second one is supply planning for which we create a model to make decisions about how much vaccine should we inoculate, backorder, procure, transport and store by using the forecast we made in the first phase and our linear model.

3.1 Demand Forecasting

3.1.1 Vaccine Survey

We conduct a survey to understand the opinions of people about getting vaccinated. The survey consists of demographic questions and questions to assess the attendees' understanding of the severity of Covid-19 outbreak as well as their affinity to take vaccines. The questions in the survey are added to Appendix A.

Our survey is distributed using Google Forms. We try to reach as many people as we can using social media tools. The survey is completed by 108 participants. 34.3 % is male and 65.7 % is female.

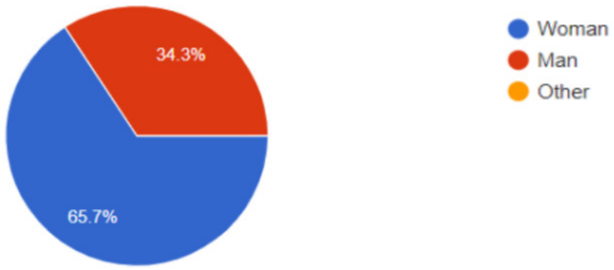

Figure 3: Gender distribution

The average of the ages is 29.95. As you can see in Figure 4, 85 % of the participants are below the age of 40. That means we have a restriction about reaching the elderly people. We do not have any participant whose age is above 63. So, forecasting the demand for the elderly people will not give accurate results.

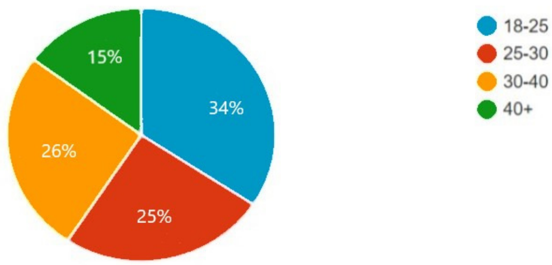

Figure 4: Age distribution

When we look at the income levels of the participants, half of them receive a salary of more than 5000 TL, while the other half receives less than this salary.

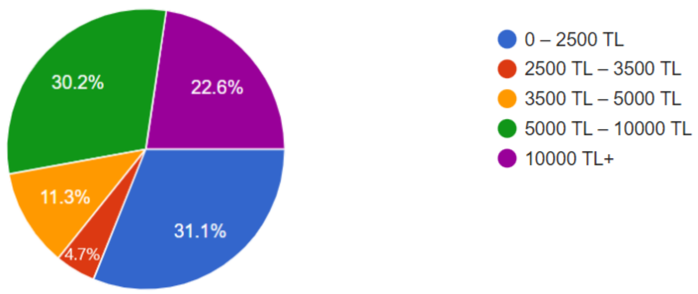

Figure 5: Income levels

In terms of education level, we can say that the participants are well-educated. We do not have a participant who has never been to school. Fifty percent of the participants have undergraduate degrees, while 28 percent have master's and doctoral degrees.

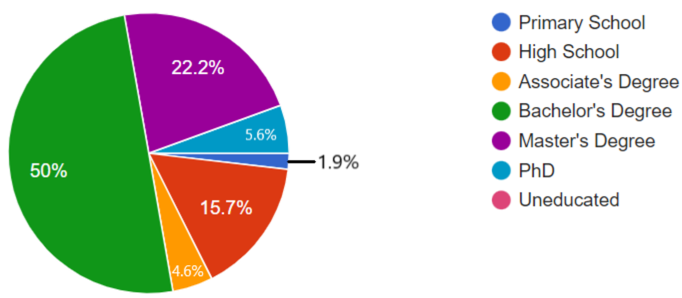

Figure 6: Education levels

While 62 percent are single, we have 38 percent married participants as shown in Figure 7:

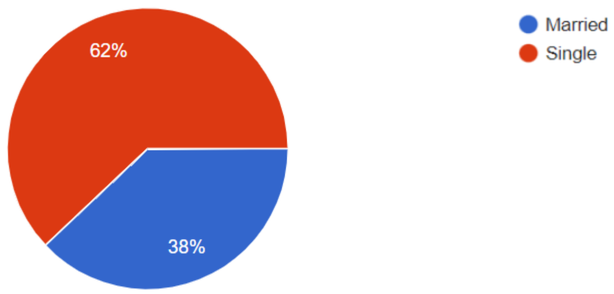

Figure 7: Marital statuses

55.7 percent of the participants are from Istanbul, followed by Ankara and Izmir with 7.5 percent. For other provinces, we have a maximum of 3 participants, which is less than 3 percent. These rates may affect the inaccuracy of our further analysis to be applied to the whole country.

When we look at the occupational groups of the participants, we can see that the highest rate is white-collar workers with 29 percent. This is followed by students with 19.6 percent. 14 percent are not working, 12.1 percent are teacher/academician, 11.2 percent are self-employed. The remaining 14 percent consists of other occupational groups; blue-collar workers, public servants, security, food and production.

To the question of what is your working style during the pandemic period, 40.6% of the respondents answered that I am going to the office. This is followed by the unemployed with 26.4%, while those who sometimes go to the office are 24.5%. As we can see from figure 8, the rate of those working from home at the time of the survey is only 8.5%.

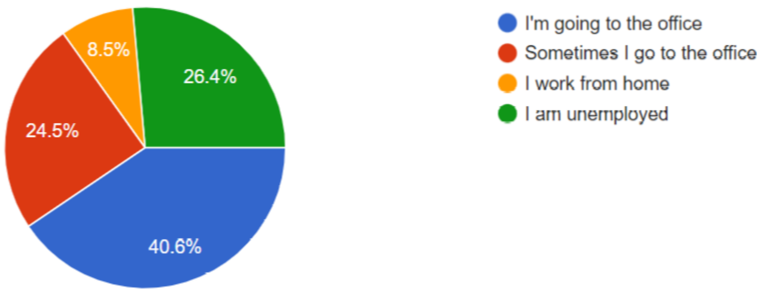

Figure 8: The way of working during the pandemic

While the rate of participants with 5 or less people in the working environment is 40.2 percent, this is followed by those with 5-20 people in the working environment with 28.9%. We can say that one third of the employees work in a crowded workplace.

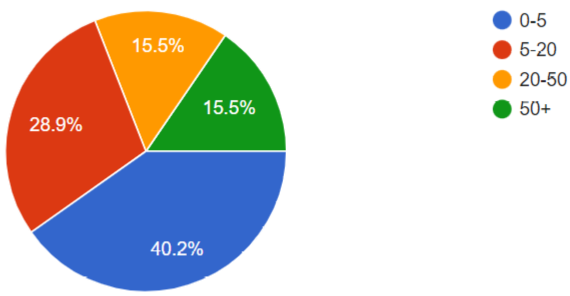

Figure 9: The number of people in the workplace

75 percent of our participants have never been diagnosed with Covid-19 before, only 25 percent have.

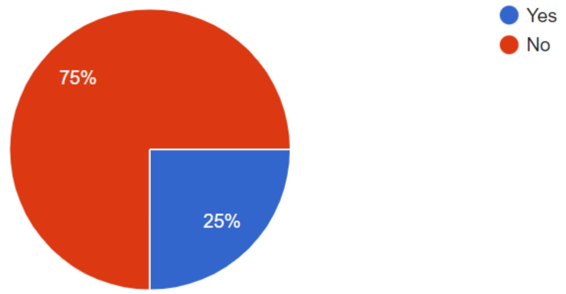

Figure 10: The rate of catching Covid-19 before

The rate of not having a family member who have been diagnosed with Covid-19 before is 45.4%. Having 3 or more family member who have been diagnosed with Covid-19 before is 25%.

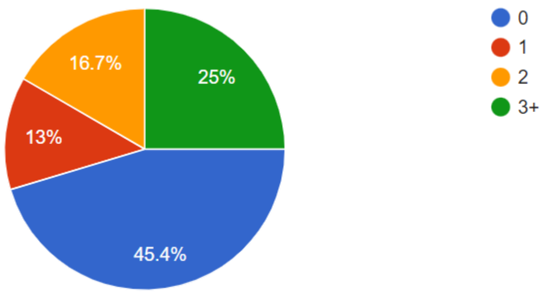

Figure 11: Family members who have diagnosed with Covid-19 before

82.4 percent of our participants do not have a chronic disease. In other words, we can say that our survey is answered mostly by people who are not in the risky group.

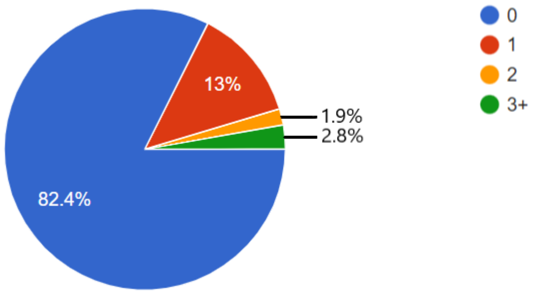

Figure 12: Number of chronic diseases

Almost half of our participants spend 6 hours or more a day outside. This is followed by those who spend a maximum of 2 hours outside with 35.2 percent.

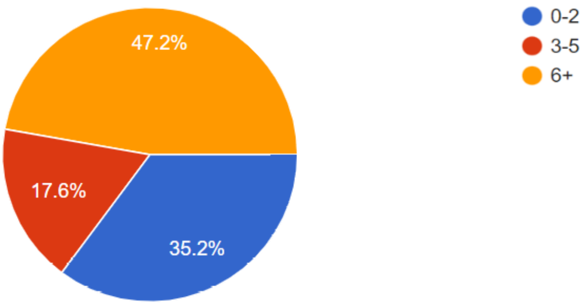

Figure 13: Hours spend outside in a day

62.6% of the participants live in the same house with 2 people or more, only 10.3 percent live alone.

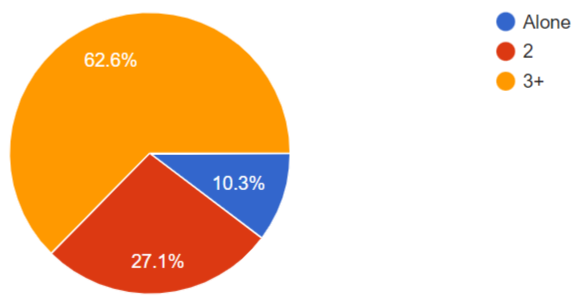

Figure 14: Number of people at home

55.7 percent of the participants say that they will definitely get vaccinated. This is followed by those who say they will definitely not, with 26.4 percent. We can say that the proportion of those who are willing to get vaccinated is higher.

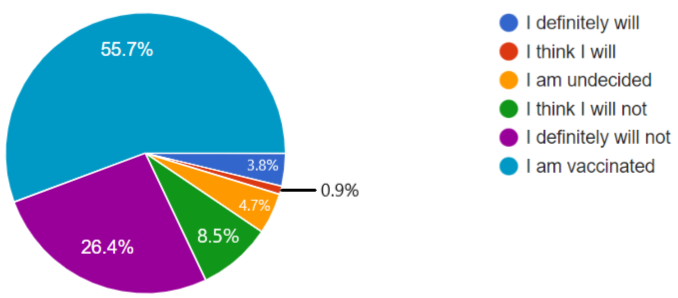

Figure 15: Vaccination decisions

44.1 percent say that the workplace asking them to get vaccinated will not affect their decisions. 33.3 percent say that this will definitely affect their decisions.

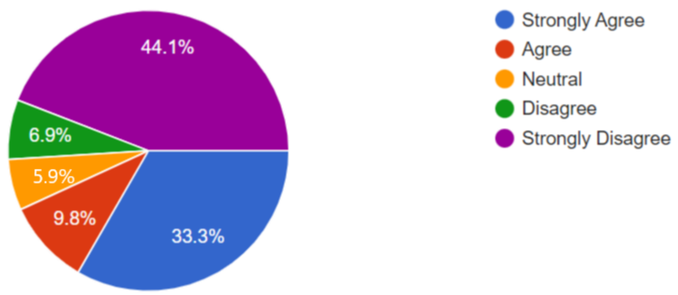

Figure 16: I would if my workplace suggested I get vaccinated

The majority of respondents think that the complications of Covid-19 are serious. 15.4 percent does not see it as serious.

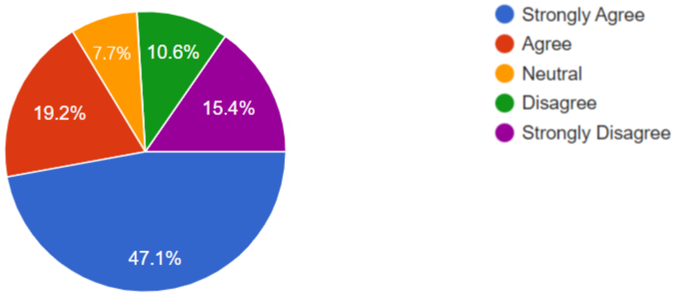

Figure 17: I think the complications of Covid-19 are serious

36.4 percent of the participants are afraid of catching Covid-19. 24.3 percent of them are also partially afraid. The rate of those who are not afraid at all is 21.5 percent.

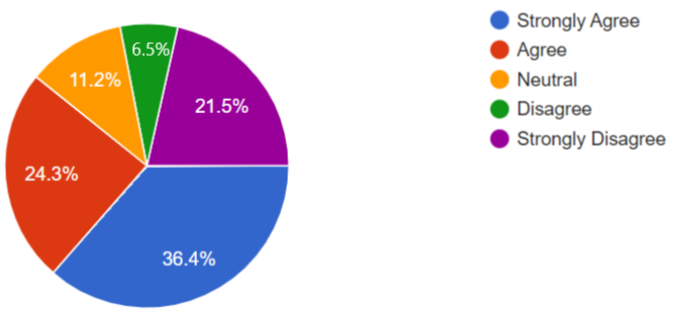

Figure 18: I am afraid of catching Covid-19

60.7 percent of respondents are afraid of infecting other people while 15 percent do not care at all.

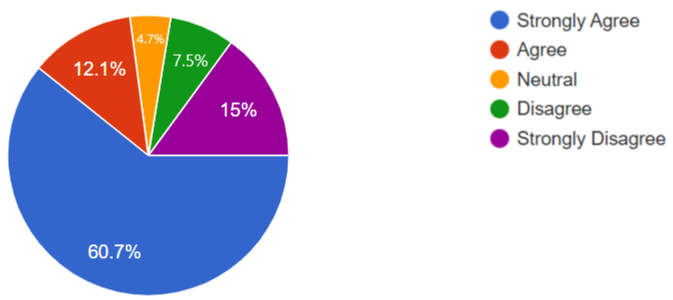

Figure 19: I am afraid of infecting others with Covid-19

The positive and negative answers to the question of whether vaccine makes them less likely to get Covid-19 or its complications are almost equally distributed.

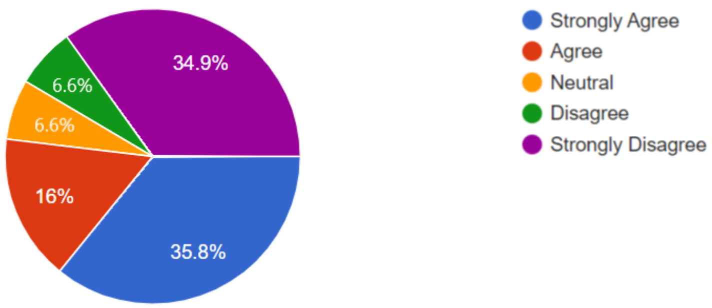

Figure 20: Vaccine makes me less likely to get Covid-19

The vast majority of respondents are concerned about the safety of the Covid-19 vaccine.

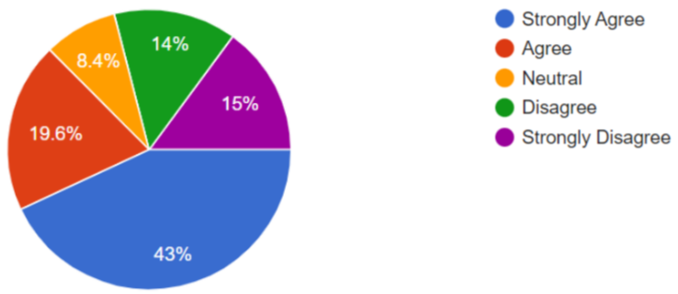

Figure 21: I am concerned about the safety of the Covid-19 vaccine

A large majority of participants are also concerned about the effectiveness of the Covid-19 vaccine.

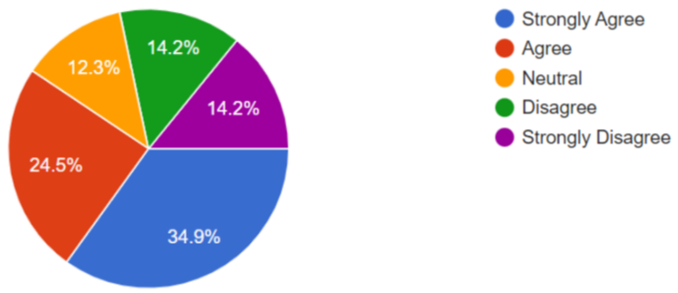

Figure 22: I am concerned about the effectiveness of the Covid-19 vaccine

The rate of participants who are worried about the side effects of the vaccine is larger with 68.3 percent.

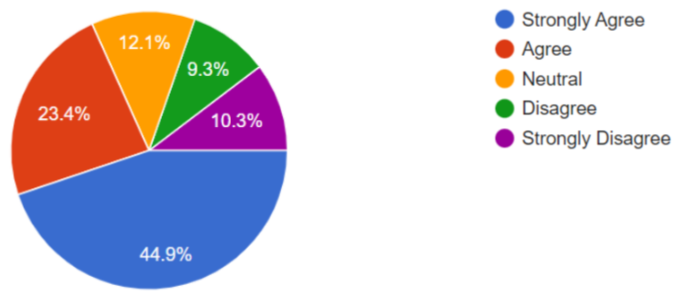

Figure 23: I am concerned about the side effects of the Covid-19 vaccine

70.7 percent state that their decision to get the Covid-19 vaccine will not be affected by the vaccination of others.

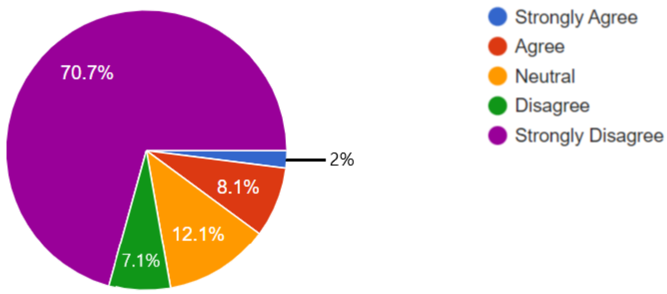

Figure 24: I will get vaccinated if many in public does

Most people do not trust the number of reported cases and deaths. This can affect their thoughts about the pandemic. If they think that the numbers announced are less than the real numbers, their concerns about Covid-19 can increase.

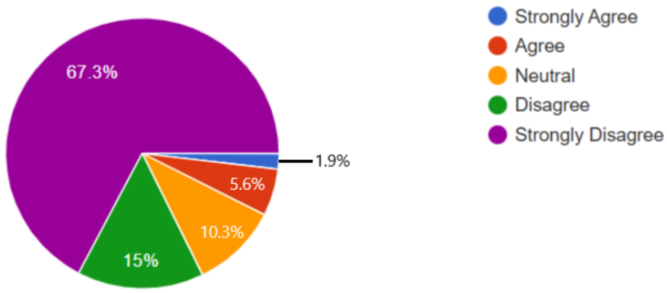

Figure 25: I trust the number of reported cases and deaths

If a vaccine is recommended by a specialist, 65 percent of the participants accept to get this vaccine.

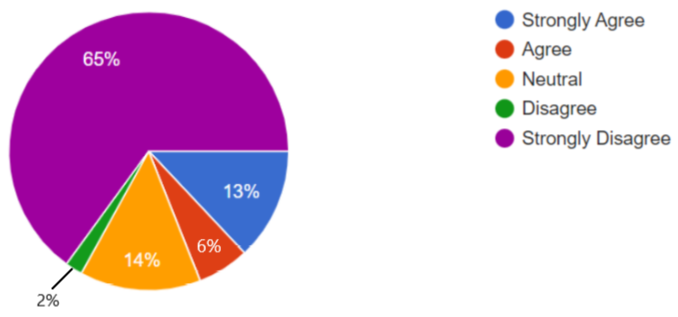

Figure 26: I have previously refused a vaccine recommended by a specialist

56.2 percent of respondents think that it is unacceptable for governments to force people to get the Covid-19 vaccine. 19 percent partly think this way. 12.4 percent consider it absolutely acceptable.

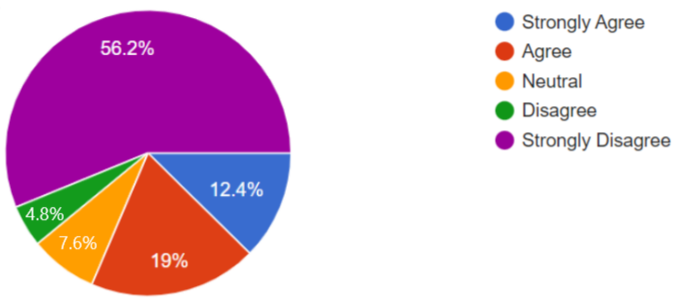

Figure 27: It is acceptable for governments to force people to get the vaccine

Half of respondents say that restrictions on unvaccinated people do not affect their choice of vaccination. 12.6 percent say that the restrictions definitely affect their decisions.

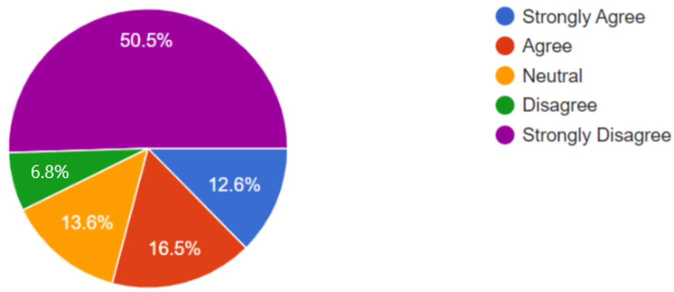

Figure 28: Restrictions on unvaccinated people affected my vaccination choice

3.1.2 Finding the Value of Desire

We need a value to measure the willingness to get vaccinated. This value can be created from the answers to the question "If you have not been vaccinated yet, are you considering getting the vaccine?". Predictions can be made using a classification or regression model. In order to remove unnecessary estimators that do not provide enough information about the willingness to get vaccinated and to overcome the curse of dimentionality, we should reduce the number of features. There are two phases of this reduction. First, we need to merge our Likert scale questions in order to have predictable dependent variables. In order to do that, we need to use a Multi-Criteria Decision-Making method. There are lots of methods but in most of them, an initial weight or a pairwise comparison of importances should be given about the features. So, this analysis would be subjective. When we search about the objective Multi-Criteria Decision-Making methods, we found two of them. They are Critic Method and Entropy Method.

Critic method uses the correlation between the features and the standard deviations of each feature to come up with a weight. It gives the greater weights to the features that has low correlation between the other features in total and the features that has high standard deviation. That means, this method accepts the features as important if they are different than the other features and if they had variety among the answers in their column.

Entropy method uses the entropy of each variable to assign weights to them. If the entropy is high, that means the answers are equally distributed and then that variable takes less weight. If the entropy is high, that means we have different answers, variable takes more weight.

In our Likert scale questions, we have ordinal data. We convert them into numbers but the difference between 1 and 2 is not equal to the difference between 2 and 3. So, we cannot treat them as numbers. Since only numbers can have a standard deviation, we should use Entropy Method to get the final weights. First of all, we normalize all the values by dividing each cell to the sum of their column. Then, we calculate the entropies by multiplying each cell with its natural logarithm. Then, we sum all the cells for each column and multiply them with -1/ln(the number of samples). We subtract these values from 1. Then, we divide them to the sum of all values. These values are our weights.

Equation (1), (2) and (3) represents the mathematical explanation of the three steps of Entropy Method. If we have m feature, n samples and the value of the i^{th} feature in the j^{th} sample is x_{ij}, the normalized value of x_{ij} is r_{ij} and can be calculated as:

$$r_{ij} = \frac{x_{ij}}{\sum_{j=1}^{n} x_{ij}} \tag{1}$$

The second step is computing the entropy value e_i of the i^{th} index:

$$e_i = -\frac{\sum_{j=1}^{n} r_{ij} \ . \ ln \ r_{ij}}{ln \ n} \tag{2}$$

The last step is computing the weight vector:

$$w_i = \frac{1 - e_i}{\sum_{i=1}^{m} 1 - e_i} \tag{3}$$

We calculate those weights and use them to calculate the value of desire to get vaccinated for each cell, in other words, for each person in our survey. We find the mean and the standard deviation of those values of only the people who have been vaccinated before. According to 3 Sigma Rule, also known as the empirical rule, there is a 99.7% chance that if the value of a person is greater than μ-3σ, he will get vaccinated. We calculate μ-3σ and use that as a threshold for getting vaccinated. Then, we turn the desire value column into a binary column using that threshold and make the column our target variable.

3.1.3 Feature Selection

After finding a way to merge the likert scale questions, we need to use a feature selection method to eliminate some of the remaining features. There are 3 feature selection methods. The first one is the Filter method. It is mostly used in data mining problems where we need to describe our data. In this method, it is not necessary to use a machine learning algorithm, only the correlation of the features with the target variable are calculated using statistical methods and features are selected according to that. After the selection, a machine learning algorithm may or may not be used. If a machine learning algorithm is tested, there would be only one model success. So, using a machine learning algorithm does not affect the feature selection process. The process of feature selection with Filter method can be seen in Figure 29. The blue nodes show where the feature selection is being made.

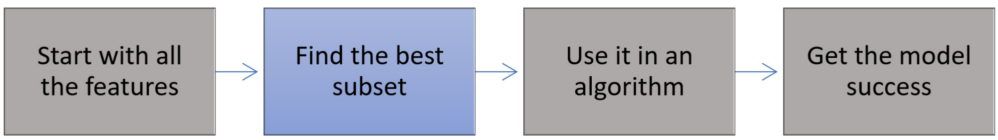

Figure 29: The feature selection using Filter Method

The second feature selection method is the Wrapper method, which is mostly used for machine learning problems. In machine learning problems, we try to learn from data and we try to make predictions according to our data using a classification or regression algorithm. And in the Wrapper Method, we try to make this prediction using different subsets of the features. That means we will select some features and use a model to make predictions, then select a different subset to do the same. After all the predictions, we will calculate the accuracy of each of them and select the feature subset that brings out the best accuracy. Filter method does not guaranty to find the best subset which gives the best accuracy. Since we will make predictions and our problem is a machine learning problem, the wrapper method is a better choice for our study. The process of feature selection with Wrapper method can be seen in Figure 30:

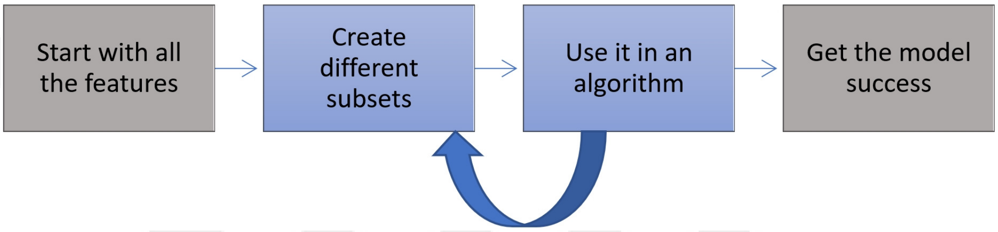

Figure 30: The feature selection using Wrapper Method

The third feature is The Embedded Method, in which the feature selection process is embedded in the model itself. This method is generally used for reducing the runtime and the complexity of the problem. Since our data was not a large one, we did not have to use this method because it does not guaranty to find the best subset which gives the best accuracy as the Wrapper Method. But it is a better method than the Filter Method for large data. The process of feature selection with Embedded method can be seen in Figure 31:

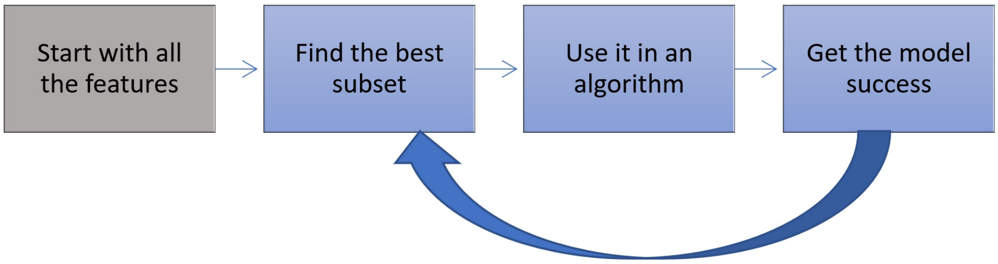

Figure 31: The feature selection using Embedded Method

We use Wrapper Method to find the best subset of the features. This method has three different searching methods: 1.Forward Selection, 2.Backward Elimination and 3.Exhaustive Feature Selection. Forward Selection starts with zero feature and keep adding the features that gives the best accuracy until we cannot get a better accuracy. Backward Elimination starts with all the features and keep removing the features until getting the best accuracy. Exhaustive Feature Selection tries all the subsets and calculate each of their accuracy using a given algorithm. Then, chooses the feature subset with the highest accuracy. This method does not overlook any feature subset. But, trying each feature subset one by one might take a long time for a data with a large feature set. In our case, we have a limited number of features. Therefore, it does not take long time to use it. That's why we used Exhaustive Feature Selection.

3.1.4 Finding the Weekly Forecast

After choosing the feature subset and the classification algorithm, we create a list that includes all combinations of features. We save and load our model to make predictions for the unknown data. We get predictions as 0 or 1 for all the combinations. Then, we try to create some rules from this classification. We group the combinations that has similar features and the same prediction. Then, we try to find the number of people in those groups in each city. We sum the number of people in the groups that have prediction 1. This is the number of people who have a desire to get vaccinated in each city. We divide this number to the population over the age of 18 to find a percentage to be likely to get vaccinated for each city.

The forecasted demand for the first dose can be found by multiplying this percentage with the number of people who have never been vaccinated before. The forecasted demand for the later doses can also be found using the previous inoculations, assuming that if someone is vaccinated he will get the later doses as well. Figure 32 shows the summary of demand forecasting:

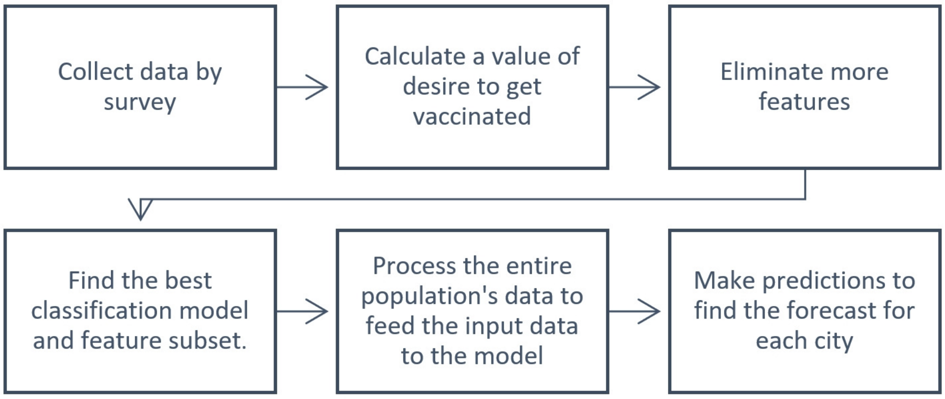

Figure 32: The summary of Demand Forecasting

As you can see in Figure 34, we collect the data by survey. We calculate a value of desire to get vaccinated for each person in our survey using the Entropy Method. Then, we eliminate some of the remaining features using the Exhaustive Feature Selection Method. We find the best classification model and the best feature subset. Then, we use the population's data to feed the model and make predictions. Lastly, we find the weekly forecast for each city.

3.2 Supply Planning

3.2.1 Vaccine Doses in Turkey

In March 2020, some coronavirus vaccines were produced and human testing began. In Turkey, the first coronavirus vaccine was given to Minister of Health Fahrettin Koca on January 14, 2021. After that, a priority list about who should be vaccinated first was shared and the process started. The first priority group in vaccination was health workers and pharmacists. After that, the residents and workers in shelters for the elderly and the disabled took the vaccine. Lastly, people over the age of 65 were vaccinated. In the second stage, employees in the sectors necessary for the continuation of the service and people with age between 50 and 65 were vaccinated. In the last stage, first people between the ages of 18-50 with chronic diseases, then healthy individuals in the same age range were vaccinated.

To be accepted as fully vaccinated, one should get at least 2 doses of vaccines. After each group of the priority list has been given permission to get vaccinated, the third (booster) dose was authorized. If one would like to become more protected, they could get the extra doses. To be able to reach the herd immunity, a region should have at least 67% vaccination rate. This rate represents the population rate who get at least two doses of vaccine. Calculations may change if it is announced that the efficiency of the second vaccine is diminished and the third vaccine is required to be considered as fully vaccinated.

3.2.2 Optimization Model

In our optimization model, we have a one year time horizon. Since, we want to create a weekly supply plan, we have 52 weeks in total. The weeks is the first index. We also consider the provinces while creating the supply plan. So, the second index is the provinces. There are relationships and specific time intervals between doses. That's why we use a dose index as well. Lastly, we think that the cities that have low vaccination rates should be prioritized for reaching the herd immunity faster and we use priority index. Our indices can be seen in Table 1:

Table 1: The indices of optimization model

Set	Index	Explanation
I	{1,2,3,...,51,52}	52 weeks of our time horizon
K	Adana,Adıyaman,...,Yozgat,Zonguldak	the provinces
D	{1,2,3,4,5}	the number of doses
P	{1,2,3,4}	priorities

The decisions that we should make in this supply chain plan is the number of vaccines inoculated, backordered, purchased, transported and the number of vaccines on hand in the locations and the central depot. Our decision variables are in Table 2:

Table 2: The decision variables of optimization model

Decision Variable	Explanation
x_{ikdp}	the number of vaccine inoculated at week i in location k, dose d and priority p
B_{ikdp}	the number of vaccine backordered at week i in location k, dose d and priority p
y_i	the number of vaccines purchased at week i
w_{ik}	the number of vaccine transported from central depot to location k in week i
I_{ik}	the number of vaccine on hand in location k at the end of week i
I_i	the number of vaccine on hand in central depot at the end of week i

The most important parameter that we should provide to our model is the forecasted demand. Reaching the herd immunity is an important aim and in the calculations we need the population over the age of 18 for each city. So, this is another parameter. We also need the costs and capacities for transportation and storage. Since we do not know the affinities for each dose, we add them as a parameter and we will do analysis by changing them. Lastly, we need the vaccination rates of each city to use in our herd immunity constraint and decide the priorities of the cities. Table 3 shows our parameters:

Table 3: The parameters of optimization model

Parameter	Explanation
f_{ikdp}	the forecasted demand of vaccine in week i in location k, dose d and priority p
a_k	the population of people over the age of 18 in location k
t_k	the transportation cost of one vaccine from the central depot to location k
s_k	the storage cost of one dose of vaccine in location k
S_k	the storage capacity of location k
TC	total transportation capacity
CDC	storage capacity at central depot
z_d	the percentage of people vaccinated with dose d-1 and want to get dose d
VR_k	the percentage of people over the age of 18 and vaccinated with at least 2 doses in location k

We model the supply planning of vaccines as a multi-objective optimization model. Given that the objectives have different priorities, we choose the lexicographic optimization method to solve this multi-objective optimization model. Our first aim is to reach the herd immunity in all cities (4).

The second important objective is to minimize the backorders; however, the minimization of backorders of the first 2 dose is more important then the minimization of backorders of the booster doses because herd immunity increases when the first 2 doses are inoculated to more people. In addition, the minimization of backorders of cities that has higher priority is more important than the backorders of cities that has less priority. In the cities that has higher priority, the vaccination rate is so low. So, we sort the backorders as backorders of dose 1 for cities that have priority 1, backorders of dose 1 for cities that have priority 2, backorders of dose 1 for cities that have priority 3, backorders of dose 1 for cities that have priority 4, backorders of dose 2 for cities that have priority 1, backorders of dose 2 for cities that have priority 2, backorders of dose 2 for cities that have priority 3, backorders of dose 2 for cities that have priority 4, backorders of dose 3 for cities that have priority 1, backorders of dose 3 for cities that have priority 2, backorders of dose 3 for cities that have priority 3, backorders of dose 3 for cities that have priority 4, backorders of dose 4 for cities that have priority 1, backorders of dose 4 for cities that have priority 2, backorders of dose 4 for cities that have priority 3, backorders of dose 4 for cities that have priority 4, backorders of dose 5 for cities that have priority 1, backorders of dose 5 for cities that have priority 2, backorders of dose 5 for cities that have priority 3 and backorders of dose 5 for cities that have priority 4. We have 20 objective functions about the backorders and we show them in a short equation as equation (5). Then, we have purchasing (6), transportation cost (7), the cost of storage in cities (8) and the storage of the central depot (9).

$$Minimize \quad Z_{herd\ immunity} = \sum_{k} h_k \tag{4}$$

$$Minimize_{d,p} \quad Z_{backorder} = \sum_{i,k} B_{ikdp} \tag{5}$$

$$Minimize \quad Z_{purchasing} = \sum_{i} y_i \tag{6}$$

$$Minimize \quad Z_{transportation} = \sum_{i,k} t_k w_{ik} \tag{7}$$

$$Minimize \quad Z_{storageofcities} = \sum_{i,k} s_k I_{ik} \tag{8}$$

$$Minimize \quad Z_{storageofcentraldepot} = \sum_{i} I_i \tag{9}$$

Subject to:

$$\text{B}_{i-1kdp} + f_{ikdp} = x_{ikdp} + B_{ikdp} \quad \forall k, p, \text{d=1} \lor d = 2 \land i < 5 \lor d \geq 3 \land i < 13 \tag{10}$$

$$\text{B}_{i-1kdp} + f_{ikdp} + z_d\, x_{i-4kd-1p} = x_{ikdp} + B_{ikdp} \quad \forall k, p, d = 2 \land i \geq 5 \tag{11}$$

$$\text{B}_{i-1kdp} + f_{ikdp} + z_d\, x_{i-12kd-1p} = x_{ikdp} + B_{ikdp} \quad \forall k, p, d \geq 3 \text{ and } i \geq 13 \tag{12}$$

$$\text{I}_{i-1k} + w_{ik} = \textstyle\sum_{d,p} x_{ikdp} + I_{ik} \quad \forall k, i \geq 2 \tag{13}$$

$$\text{w}_{ik} = \textstyle\sum_{d,p} x_{ikdp} + I_{ik} \quad \forall k, i = 1 \tag{14}$$

$$\text{I}_{i-1} + y_i = \textstyle\sum_{k} w_{ik} + I_i \quad \forall i \geq 2 \tag{15}$$

$$\text{y}_i = \textstyle\sum_{k} w_{ik} + I_i \quad \forall i = 1 \tag{16}$$

$$\textstyle\sum_{k} w_{ik} \leq TC \quad \forall i \tag{17}$$

$$\text{I}_i \leq CDC \quad \forall i \tag{18}$$

$$\text{I}_{ik} \leq S_k \quad \forall i, k \tag{19}$$

$$\text{VR}_k + (\textstyle\sum_{i,p} x_{ik2p})/a_k + h_k \geq 0.67 \quad \forall k \tag{20}$$

$$\text{x}_{ikdp}, B_{ikdp}, y_i, w_{ik}, I_{ik}, I_i \geq 0 \quad \forall i, k, d, p \tag{21}$$

We have two decision variables about the number of vaccines. The one with x represents the number of vaccines actually inoculated and the one with f represents the forecasted demand of vaccines. The variable f is calculated for each dose d and we need to consider it in every week i as the weekly demand. By adding this f variable to the backorder from the previous week *i-1*, we can find the total demand. And if we inoculate x_{ikdp} vaccines in week i and supply this demand as much as we can, the remaining demand would be our backorder for week i. The constraint (10) explains this relation for demand for the first dose or demand for the second dose in the first 4 week or demand for the later doses in the first 12 weeks. For the given ranges, we need to consider only the forecasted demand and inoculated vaccines since we do not have any second inoculation as a continuation of the previous dose in those ranges.

For the second dose, we can have forecasted demand and inoculated vaccines for weeks 5 and later. In addition, we should include the second inoculations for dose 2 which depends on the inoculated vaccines before 4 weeks in our planning horizon since 4 week is the recommended time between the first and the second dose. This logic is written in the constraint (11).

Constraint (12) also shows that for the later doses we can have forecasted demand and inoculated vaccines. In addition, we should include the third or later inoculations which depend on the inoculated vaccines before 12 weeks in our planning horizon since 12 week is the recommended time between the doses after 2.

Constraint (13) is an inventory balance equation for each location k. If we add w_{ik} (the number of vaccine transported from central depot to location k in week i) to I_{i-1k} (the number of vaccine on hand in location k at the end of week *i-1*), we can find the total inventory at the beginning of week i. If we inoculate x_{ikdp} vaccines at week i in location k for all d, the remaining vaccines would be our I_{ik} (the number of vaccine on hand in location k at the end of week i).

Since we do not have any backorder left from the previous week in week 1, we add the same equation without I_{i-1k} for week 1 as constraint (14).

Constraint (15) is and inventory balance equation for our central depot. As in the previous constraint, if we add y_i (the number of vaccine purchased at week i) to I_{i-1} (the number of vaccine on hand in the central depot at the end of week *i-1*), we can find the total inventory at the beginning of week i. If we transport w_{ik} vaccines from central depot to location k's in week i, the remaining vaccines would be our I_i (the number of vaccine on hand in the central depot at the end of week i).

For week i, we do not have any backorder left from the previous week. So, we add the same equation without I_{i-1k} for week 1 as constraint (16).

The sum of vaccines transported from central depot to location k's in week i should be less than or equal to TC (total transportation capacity) in each week i. Constraint (17) represents this equality.

There is a storage capacity at the central depot (CDC) and the sum of I_i (the number of vaccine on hand in the central depot at the end of week i) should be less than or equal to this storage capacity as stated in Constraint (18).

Constraint (19) asserts that there is a similar storage capacity for each location k and the sum of vaccines on hand in location k at the end of week i should be less than or equal to S_k (the storage capacity of location k).

Constraint (20) emphasizes that the sum of vaccines inoculated at week i's in location k's which are dose d and priority p divided by a_k (the population over the age of 18 in location k) gives us the vaccination rate of location k and it should be greater than or equal to 0.67 because 0.67 is the minimum required vaccination rate to reach the herd immunity. We add slack variables h_k for all location k's in this constraint and we try to minimize them in our objective function in order to have a vaccination rate not only greater than 0.67 but also the maximum number we can get with this optimization model.

Last constraint (21) is the non-negativity constraint for our decision variables.

3.2.3 Input Data Preperation

We find the demand for dose 1 by multiplying the value of desire to get vaccinated with the number of people who have never been vaccinated before and over the age of 18. We assume that all of the demand for dose 1 would be in week 1. The demand for dose 2 can be calculated by assuming that it is equal to the number of vaccines inoculated 4 weeks ago. The demand for dose 3 can be calculated by assuming that it is equal to the number of vaccines inoculated 12 weeks ago. The demand for dose 4 can also be calculated by assuming that it is equal to the number of vaccines inoculated 12 weeks ago. Since the number of vaccines inoculated so far is at most the third dose in our data, we could only have forecasts for the first 4 doses.

These calculated forecasts have week information, location information and dose information. The only missing information to create our parameter f_{ikdp} is the priority information. If our aim is to end the pandemic and consequently reach the herd immunity, the vaccination rates are so important. That's why we use the vaccination rates of the cities to find the priorities. The Turkish Ministry of Health had already grouped cities in red, orange, yellow and blue according to vaccination rates. So, we use those groups as priorities. Each city has only one priority. And we can create our parameter f_{ikdp} with all this information.

Parameter a_k (the population over the age of 18 for city k) can be taken from the data served by Turkish Statistical Institute. For the transportation cost, we assume that the central depot is in Ankara and the distance of each city from Ankara can be counted as the transportation cost. For the storage cost, we divide the population to the number of hospitals. This value shows how many people are admitted to each hospital. And if this value is high, that means the storage is not enough in that city. We group the cities according to this value. We have the vaccination rate for each city. This parameter can be found by dividing the number of people who have inoculated with at least 2 doses to the population over the age of 18 for city k. Lastly, we have affinities, transportation capacity, storage capacity of the locations and the central depot. Since we do not have any information about them, we try different values.

To sum up, we model the vaccine supply chain as a multi-objective optimization model. We calculate the parameters that we can calculate and we try different values for the ones that we do not have any information about and make our analysis. We use Python and Gurobi for getting the solution.

CHAPTER IV

RESULTS

As we stated in the Vaccine Survey section, we conduct a survey to understand the oppinions of people about getting vaccinated. We have Likert scale questions that need to be merged. In order to have one value that can replace all the Likert scale quesions, we have to calculate the weights of these questions. We use Entropy Method to get those weights.

In the Entropy Method, we normalize the data, calculate the entropies and find the weights using Equation (1), Equation (2) and Equation (3). The weights of the questions, from the most important to the least, can be seen in Table 4:

Table 4: Questions and their weights from most important to least important

ID	Weight	Question
Q12	0.1005	It is acceptable for governments to force people to get the vaccine.
Q1	0.0919	If my place of work recommends that I get vaccinated, I will.
Q13	0.0887	Restrictions on non-vaccinated people will/have affected my choice.
Q6	0.086	I am concerned about the safety of the Covid-19 vaccine.
Q9	0.0809	I will only get the vaccine if it is taken by many people in public.
Q8	0.0806	I am concerned about the side effects of the Covid-19 vaccine.
Q5	0.0801	The vaccine makes me less likely to get Covid-19 or its complications.
Q7	0.0742	I am concerned about the effectiveness of the Covid-19 vaccine.
Q10	0.073	I trust the number of reported cases and deaths.
Q14	0.0657	If you have not been vaccinated yet, will you get vaccinated?
Q3	0.0532	I am afraid of catching Covid-19.
Q2	0.0468	I think the complications of Covid-19 are serious.
Q4	0.0415	I am afraid of infecting others with Covid-19.
Q11	0.0368	I have refused a vaccine, even though it was recommended.

The most three important questions show that if a person thinks that the government has a right to force people to get vaccinated, he gets vaccinated. And if the government or the workplaces force people to get vaccinated with sum restrictions, people get vaccinated.

By looking at the least important questions we can say that even if a person thinks that the complications of Covid-19 are serious, it does not affect their vaccination decision that much. People do not care infecting other people. And rejecting other vaccines does not cause the rejection of Covid-19 vaccine.

By multiplying these weights with their actual values and summing them up, we calculate a value between 1 and 5 that expresses the desire to get vaccinated for each person in our survey. Then, we find the mean and the standard deviation of those values for only the people that are already got vaccinated. The mean is 3.439 and the standard deviation is 0.617. With the help of the three-sigma rule, we can say that there is a 99.7% chance that if the value of desire to get vaccinated of a person is greater than 1.5873, which is μ-3σ, that person will get vaccinated. We changed our desire value column into a binary column using this threshold and make it our target variable.

After turning our problem into a binary classification problem, we use Exhaustive Feature Selection Method to find the best classification model and the best subset. In this method, we need to try different models and compare their success with different feature subsets. Since, we want to predict whether a person will get vaccinated or not, this is a classification, not a regression. So, we need a classification algorithm. We try Naive Bayes, Logistic Regression, K-Nearest Neighbours, Decision Tree and Random Forest. We measure their performances using accuracy, F-measure, Precision, Recall and Area Under Curve values using Weka Software. We come up with eleven choices.

Since, we do not know the exact number of people in each feature combination group, we are able to multiply their percentages. When we do that, there should be no independent features. So, we calculate the pairwise correlation of the features. Age has a high correlation with income level and marital status. Also, income level had a moderate correlation between gender and the number of people at home. So, we eliminated those choices which includes two highly correlated features. We also eliminated the ones that has worse values according to our metrics. The used metrics are true positive rate, false positive rate, precision, recall, F-measure, Matthew's correlation coefficient, ROC area and PRC area. Best three choices have the same accuracy as 76.4151% and their other scores can be seen from Table 5:

Table 5: Comparison of classification algorithms

Algorithm	Class	TPR	FPR	Precision	Recall	F	MCC	ROC	PRC
Naive Bayes	0	0,310	0,065	0,643	0,310	0,419	0,323	0,658	0,439
Naive Bayes	1	0,935	0,690	0,783	0,935	0,852	0,323	0,658	0,804
Naive Bayes	Avg.	0,764	0,519	0,744	0,764	0,733	0,323	0,658	0,704
Logistic Reg.	0	0,276	0,052	0,667	0,276	0,390	0,315	0,690	0,488
Logistic Reg.	1	0,948	0,724	0,777	0,948	0,854	0,315	0,690	0,819
Logistic Reg.	Avg.	0,764	0,540	0,747	0,764	0,727	0,315	0,690	0,728
Decision Tree	0	0,345	0,078	0,625	0,345	0,444	0,332	0,571	0,401
Decision Tree	1	0,922	0,655	0,789	0,922	0,850	0,332	0,571	0,751
Decision Tree	Avg.	0,764	0,497	0,744	0,764	0,739	0,332	0,571	0,655

Since their accuracies are equal, we looked at the other metrics. We found the best scores and Logistic Regression has the most best scores. Logistic Regression is the most used classification algorithm for binary classification as well. So, we decided to continue with Logistic Regression. The selected feature subset for Logistic Regression includes household size and age.

After choosing the feature subset and the classification algorithm, we create a list that includes all the combinations of features. We save and load our model in Weka software to make predictions for the unknown data. According to the predictions of our model, if a person lives alone, he gets vaccinated. If a person lives with 1 person and his age is less than 64, he gets vaccinated. And if a person lives with 2 or more people and his age is less than 41, he gets vaccinated. Table 6 shows this result:

Table 6: Prediction groups according to household size and age

Household size/age	18-41	42-63	64+
1	1	1	1
2	1	1	0
3+	1	0	0

When we look at our data, we can see the actual percentages for the subgroups. Table 7 shows number of people who want to get vaccinated in the group / number of people in the group. Last column shows the same thing for people in all the ages according to their household sizes. For people aged 18-41, those who want to get vaccinated in all subgroups are high in percentage. And our model accepts these groups as they all will get vaccinated. People aged 42-63 have 1 person with a household size of 1 and 1 person with a household size 2. These two people are willing to get vaccinated. That's why our model accepts them as they all will get vaccinated. For people aged 42-63 and have a household size of 3 or more, those who want to get vaccinated are low in percentage. Therefore, our model predicts that this subgroup will not be vaccinated. Since we do not have a 64-year-old or older participant, our model makes use of household size distributions when making predictions about them. When we look at all age groups, the percentage of people who want to get vaccinated is 92% for people that have household size 1, 86% for people that have household size 2 and 63% for people that have household size 3 and more. Although the rate of those who want to get vaccinated is high in all the groups in this age range, our model predicts that only the first group will get vaccinated, while the other groups will not. Since we make predictions with limited data, we cannot argue that the predictions are completely correct. Much more accurate results can be obtained by using more data.

Table 7: The actual data of prediction groups

Household size / age	18-41	42-63	64+	All the ages
1	10/11	1/1	-	11/12
2	23/27	1/1	-	24/28
3+	39/54	3/12	-	42/66

We know the age distribution by city from Turkish Statistical Institute. We also know the household size distribution by province. Since all the participants of our survey is over the age of 18, the correlation between age and the number of people at home is 0.053 according to our data. Thus, the dependence is negligible and we can accept them as independent. So, we count the number of people whose age is between 18 and 41, between 42 and 63, greater than 63. Then, we convert the household size data to percentages and we multiply them with the number of people in each age group. We come up with the numbers for each cell in our result table for each city. Then, we sum the corresponding cells and found the number of people who are likely to get vaccinated and who are not for each city. The percentage to be likely to get vaccinated for each city could be found by dividing the number of people who are likely to get vaccinated to the population over the age of 18.

The demand for the first dose could be found by multiplying this percentage with the number of people who have never been vaccinated before in each city. We assume that all of those demands will occur in the first week. The demand for the second dose is equal to the number of vaccinations of dose 1 before 4 weeks. So, we can have predictions for dose 2 in the first 4 weeks of our planning horizon. The demand for the third or later doses is equal to the number of vaccinations of the previous dose before 12 weeks. So, we can have predictions for the third or later doses in the first 12 weeks of our planning horizon. The calculations can be seen in Appendix B.

With the help of these calculations, we have i,k and d values in our parameter f_{ikdp}. The only missing part is the priority index and that's why we use the vaccination rates of the cities to find the priorities. The Turkish Ministry of Health had already grouped cities in red, orange, yellow and blue according to vaccination rates. So, we use those groups as a priority rate. Each city has only one priority rate. And we could create our parameter f_{ikdp} with all of this information.

Parameter a_k (the population over the age of 18 for city k) is taken from the data served by Turkish Statistical Institute [21]. For the transportation cost, we assume that the central depot is in Ankara and the distance of each city from Ankara can be counted as the transportation cost. For the storage cost, we divide the population to the number of hospitals. This value shows how many people are admitted to each hospital. And if this value is high, that means the storage is not enough in that city. We group the cities according to this value. The number of hospitals, population over the age of 18, population per hospital, storage cost, transportation cost, the population who get at least 2 doses, vaccination rate and priority of each city can be seen from Appendix C.

Lastly, we have values that we do not have information about which are the affinities, transportation capacity, storage capacity of the locations and the central depot. In the beginning, we assume that if a person get vaccinated for the first dose, he will get all the remaining doses. That means the affinities for the next dose is one for all doses. Since we do not have any information about transportation capacity, storage capacity of the locations and storage capacity of the central depot, we use an initial value of 10000.

In our first run, we put the backorder function first, followed by the herd immunity function. Then we add purchasing, transportation and storage functions. But in this case, our model try to reduce the backorders and since the equations of the 1st dose are at the top, it also tries to reduce the backorders of initial doses of the cities with low priority, high vaccination rate. Reducing the backorders of the cities with low priorities cannot improve the herd immunity. Because those cities already have vaccination rates higher than 0.67. That's why we decide to put the herd immunity function first. In this case, the optimal value of the herd immunity function, the number of cities that could not reach the herd immunity, the backorders of the second doses for cities that have priority 1 and 2 decrease. On the other hand, the transportation cost and total backorders increase. The comparison of these two cases with their actual values can be seen in Appendix D. A comparison by percentage is in Figure 33:

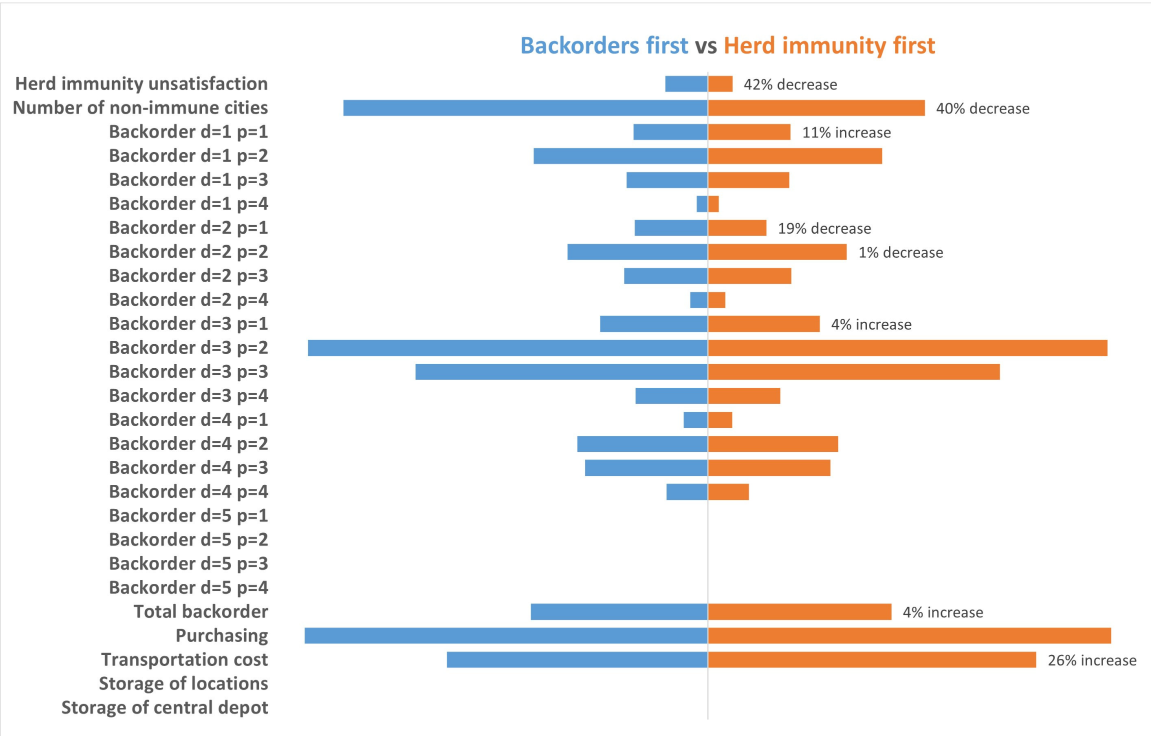

Figure 33: The comparison of prioritizing backorders and herd immunity

The second case where we put the herd immunity function first is more suitable for us because our main aim is to end the pandemic by reaching the herd immunity. Minimizing the backorders of doses that cannot contribute to the decrease in the herd immunity function is not as important as the herd immunity function itself. So, we decide to continue our analysis with the case where the herd immunity function is the most important objective function.

We start by increasing the capacity of the central warehouse. This increase does not change any of our values. We find this logical because we do not keep storage in the central warehouse with the current capacity values. The storage in our central depot is always zero. We send all the vaccines we receive to the locations immediately. In addition, increasing the storage capacity in the locations alone does not change our values. As in the central warehouse, our storages in the locations are zero with our current values. We can say that we use all the vaccines that reach the locations immediately.

Increasing transportation capacity alone changes our values. For example, when we look at the optimal value of the herd immunity function, this value becomes zero when the transportation capacity is increased 9 times. Figure 34 shows the herd immunity unsatisfaction change when we increase the transportation capacity:

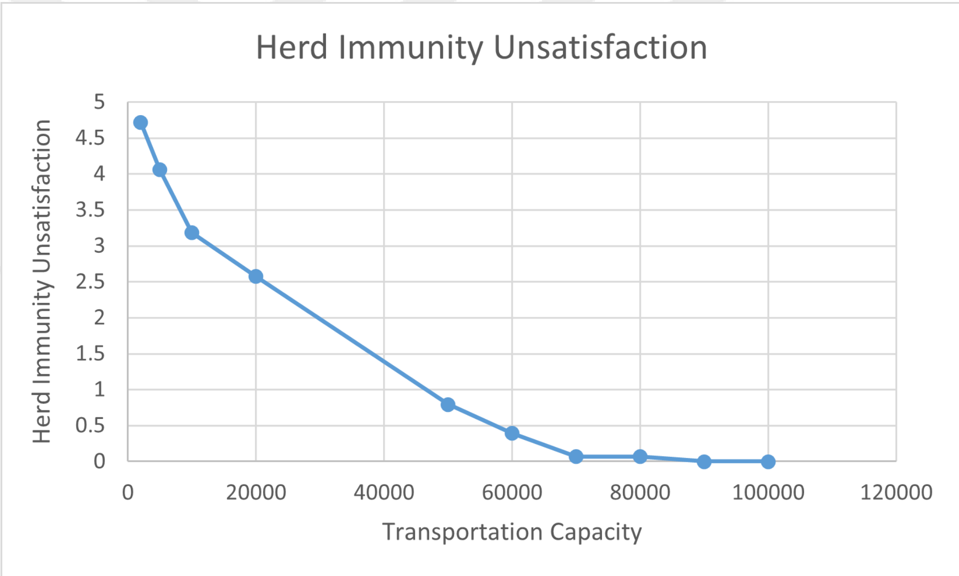

Figure 34: Herd immunity unsatisfaction according to transportation capacity

The number of cities that cannot reach herd immunity is 41 with our initial values. When the transportation capacity is increased 9 times, it becomes zero. When the transportation capacity is increased 5 times, the number of cities that cannot reach herd immunity is 5. These cities are Bursa, Diyarbakır, İstanbul, Konya and Şanlıurfa. They have high priority rates and low vaccination rate. When the transportation capacity is increased to 6 times, the number of cities that cannot reach herd immunity decreases to 2. These cities are İstanbul and

Şanlıurfa. Bursa, Diyarbakır and Konya reach herd immunity. When the transportation capacity is increased 7 times, there is only one city that cannot reach herd immunity. That city is Istanbul. In other words, we can say that since the population of Istanbul is very high, it is necessary to do a lot of vaccination to increase the vaccination rate there. The vaccination rate of other cities can be increased by vaccinating fewer people. Therefore, our model leaves the vaccinations of Istanbul for the last. Figure 35 shows the number of non-immune cities when we increase transportation capacity:

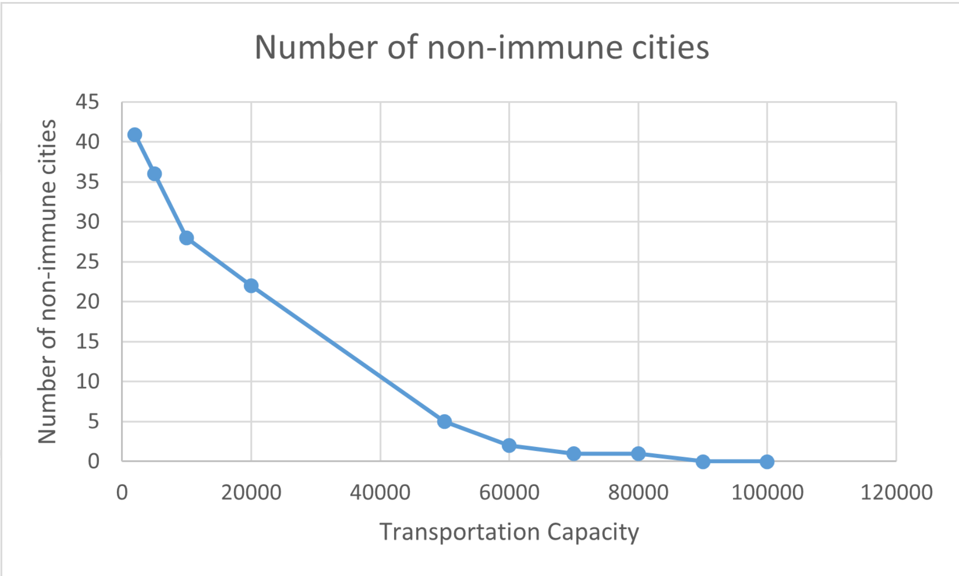

Figure 35: Number of non-immune cities according to transportation capacity

When we increase the transportation capacity, we can send more vaccines because we do not get stuck in the storages. So, we buy more vaccines and decrease total backorders. When the transportation capacity increases 1304 times, our total backorder becomes 0. However, increasing the transportation capacity 1304 times can be very costly. Since the slope of the change curve decreases too much after 4 million, this increase may be sufficient for us. Figure 36 shows total backorders:

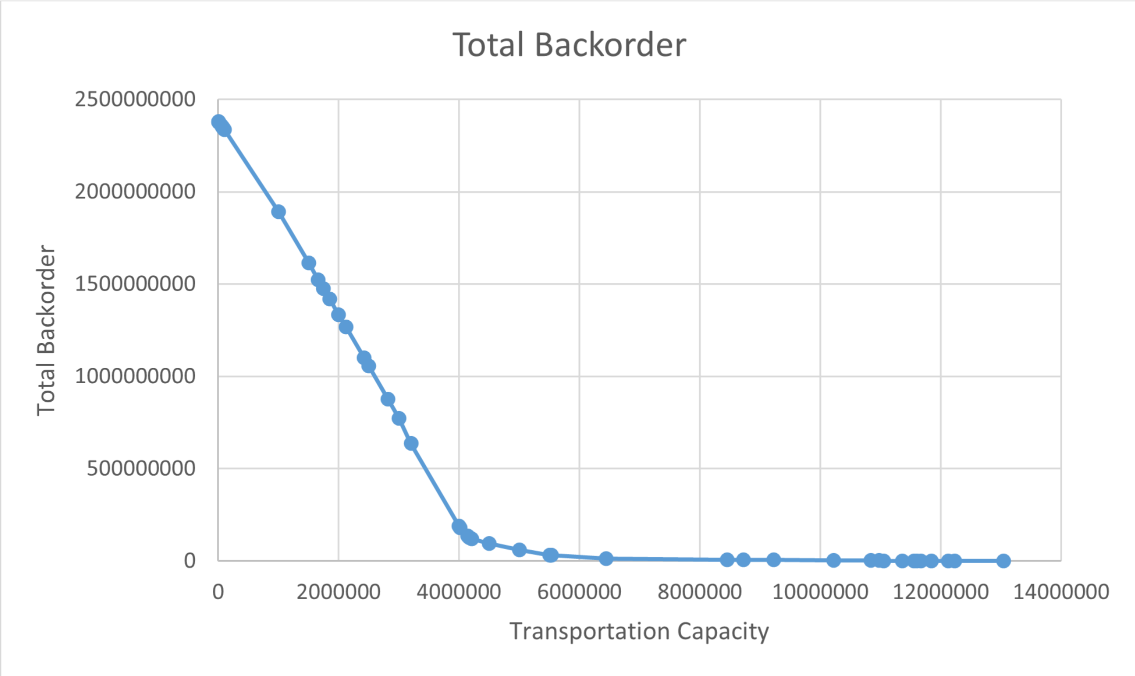

Figure 36: Total backorders according to transportation capacity

Our purchasing is equal to our total transportation capacity in our one year time horizon, that is, weekly transportation capacity times 52. When our transportation capacity is increased 320 times, purchasing becomes 166.3 million and does not change after that. It does not change even when herd immunity and backorder values are all zero. We initially forecast 50 million demand. There are also new demands arising from the vaccines inoculated in our planning horizon. This means that this purchase is enough to meet all the demand, demand that we forecast before and will occur during the one year time horizon. When we increase transportation capacity 320 times and increase it 1304 times, we buy the same number of vaccines. However, in the first case we send these vaccines more slowly. So, we start to store the vaccines and cannot set all backorder values to zero. In the second case we send the vaccines faster and the storages decrease. Figure 37 shows the purchasing:

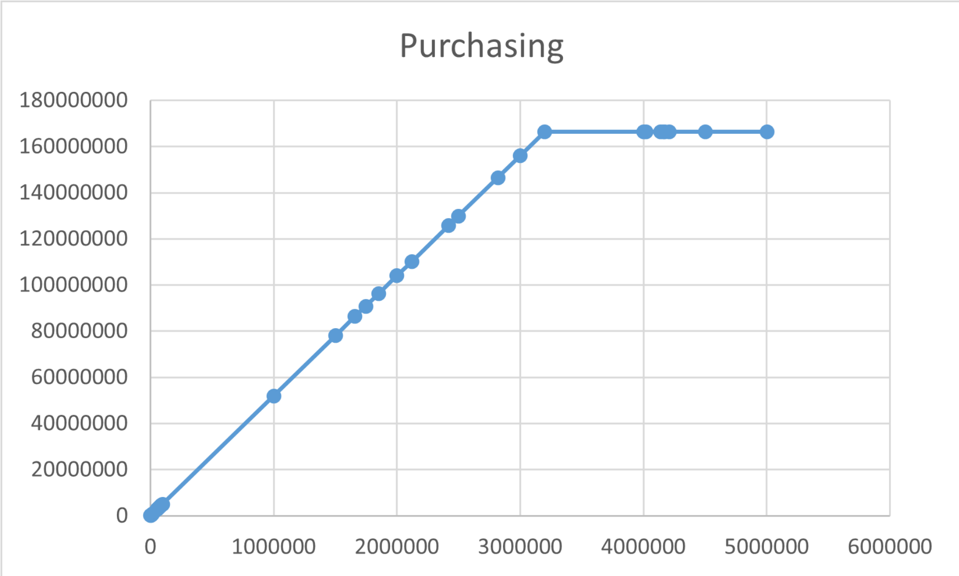

Figure 37: Purchasing according to transportation capacity

As our transportation capacity increases, so does our transportation cost. When the transportation capacity increases 320 times, our transportation cost becomes 85 billion and does not change after that. As with the purchase, transporting vaccines at this cost is sufficient to meet all demand. Figure 38 shows the cost of transportation:

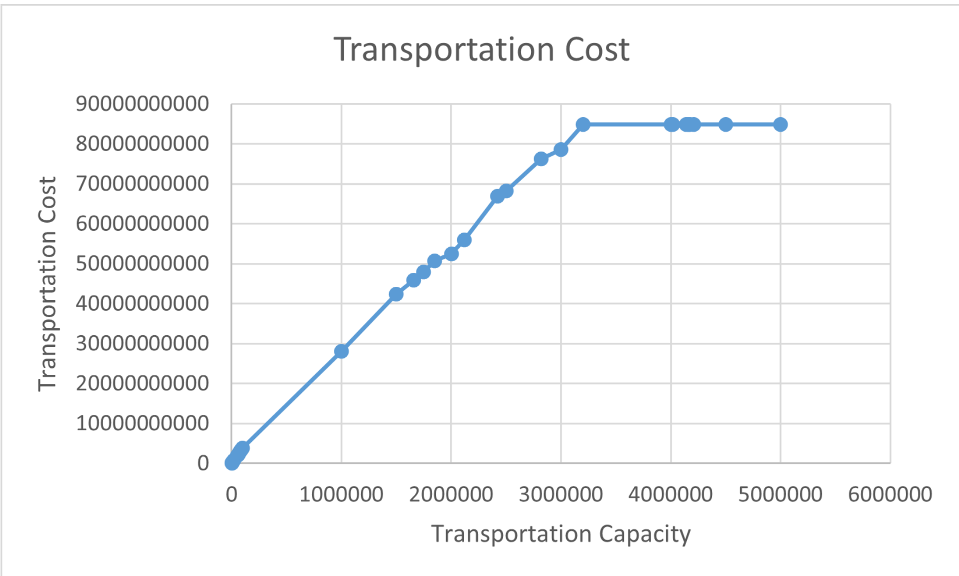

Figure 38: Transportation cost according to transportation capacity

When we increase the transportation capacity 421 times, we start to make storage in the provinces. This storage is increasing until we increase the transportation capacity 552 times. After that, the storage starts to decrease. When we increase the transportation capacity 1304 times, it becomes zero again.

After purchasing and transporting enough vaccines to meet all our demands, the number of purchased vaccines and the transportation cost does not change. Until they are fixed, we are purchasing as much as the total vaccine we could send. After these two are fixed, the only thing that changes is when the vaccines are sent. When the transportation capacity increases slightly, it causes more vaccines to be transported in the first weeks. Since the demand caused by the inoculations in our planning horizon has not yet occurred, we start storing and wait for that demand to occur. As the transportation capacity increases, the storage in the provinces also increases. When the transportation capacity increases even more, the transportation capacity parameter becomes very flexible. Since we are not stuck on transportation capacity, we send the vaccines when demand occurs. That's why the storages are decreasing. Figure 39 shows the total storage in cities:

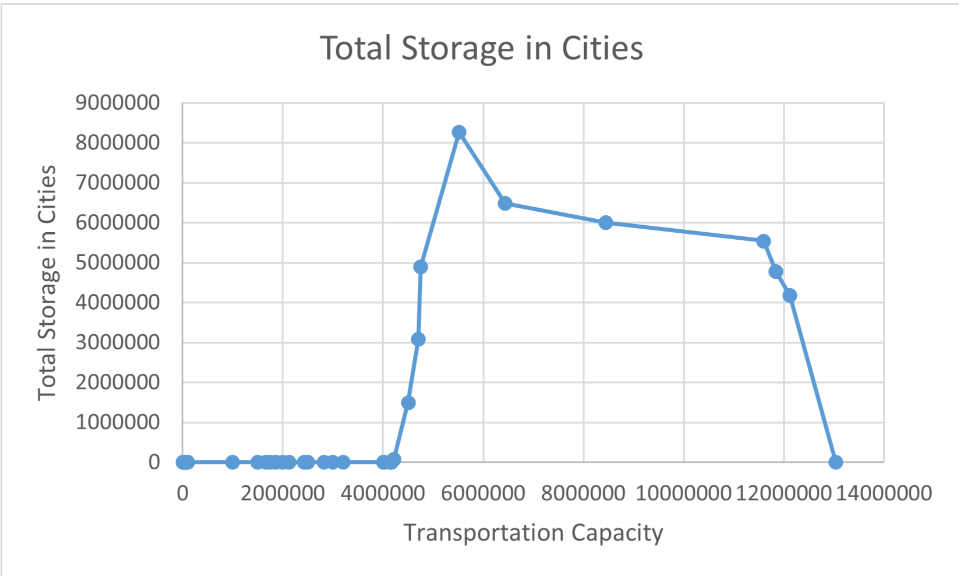

Figure 39: Total storage in cities according to transportation capacity

The places where the objective functions become zero are also important for us because it can give an idea about how the transportation capacity increase affects the functions and how much increase can be satisfactory. Figure 40 shows those capacity values for the functions that have values greater than zero at the beginning and can be minimized to zero:

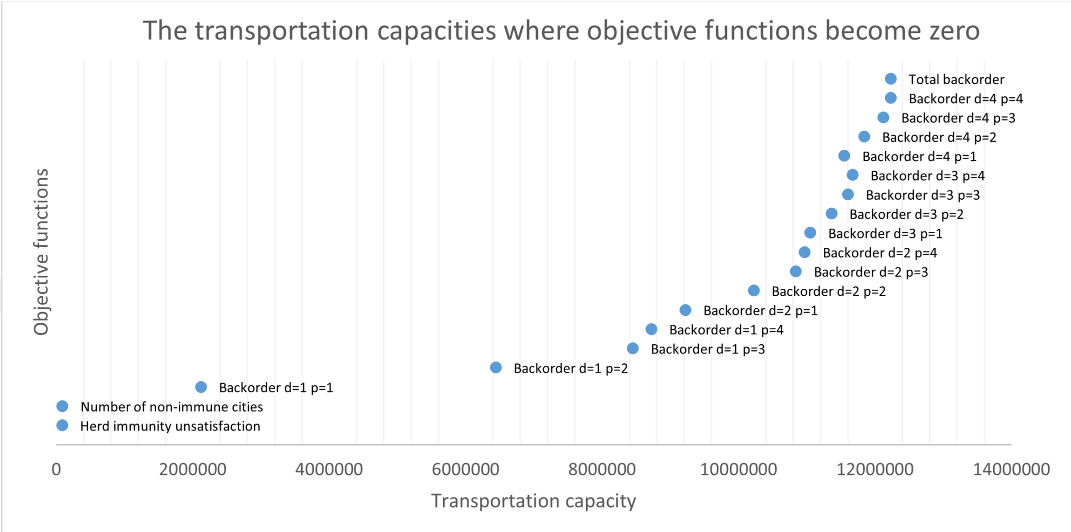

Figure 40: The transportation capacities where objective functions become zero

As you can see, even just to meet the demand for the first dose, we need to increase transportation capacity 872 times. This can be very costly and reaching the herd immunity is more important than minimizing the backorders.

Lastly, we try different affinity rates and see their affects on our main aim, herd immunity. We have defined the z_d parameter related to the affinities. The percentage of people vaccinated with dose 1 and want to get dose 2 can be represented as z_2. We should have a list including z_2, z_3, z_4 and z_5. At the beginning, we assume that all the affinities are equal to 1. That means, if someone is vaccinated with a dose, he will get all the later doses. In this case, increasing transportation capacity 1304 times makes all the backorders and herd immunity function zero. If we change z_3, z_4 and z_5, our purchasing and transportation capacity are decreasing. But we are still able to make all the backorders and herd immunity function zero. The only thing that changes the herd immunity is changing z_2. When we change

z_2, we can still make the backorders zero but some of the cities cannot reach the herd immunity. For example, if all the affinities are zero, that means there is only forecasted demand, 16 cities cannot reach the herd immunity. And the optimal value of the herd immunity function is 0.863108. When we keep increasing z_2, the purchasing and transportation cost increases slightly. However, the herd immunity is getting better. Figure 41 shows the herd immunity unsatisfaction for different values of z_2:

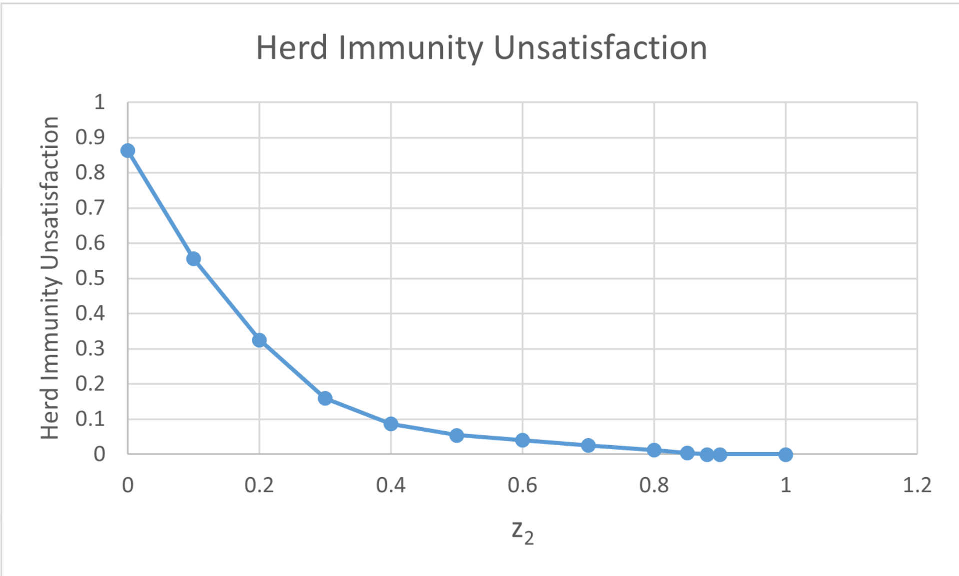

Figure 41: Herd immunity unsatisfaction according to z_2

When z_2 is equal to 0.88, we are able to reach the herd immunity in all the cities. That means, we need z_2 to be greater than or equal to 0.88. In this case, even if z_3, z_4 and z_5 are zero, we can reach the herd immunity in all the cities. If z_2 is less than 0.88, we will always have at least one city that cannot reach the herd immunity. Figure 42 shows the number non-immune cities for different values of z_2:

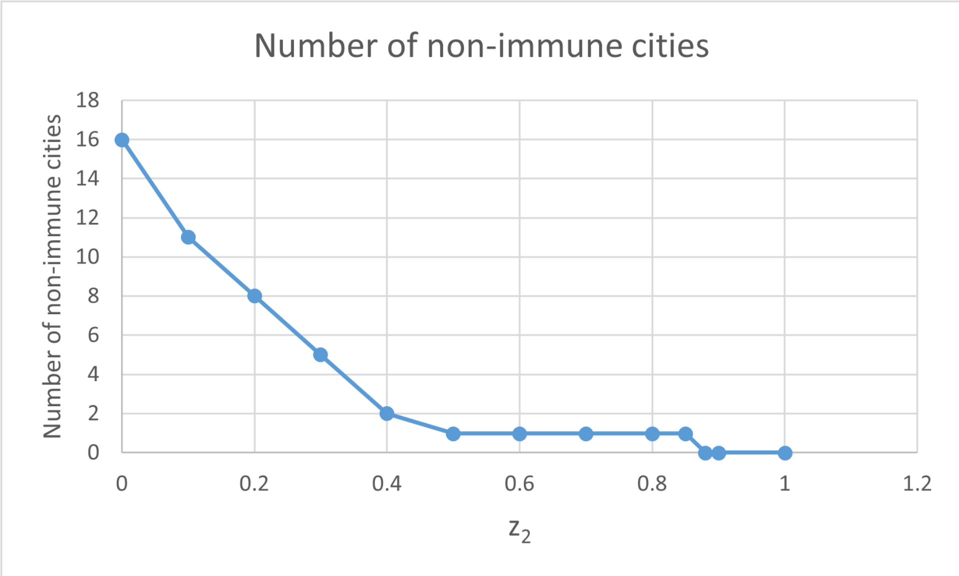

Figure 42: The number non-immune cities according to z_2

Considering all the changes, it may seem like the best option is to increase the transportation capacity as much as we can, but it can be very costly. After the number of vaccines we purchase and the transportation cost are fixed (transportation capacity is 3.2 million), before we start holding storage (transportation capacity is 4.2 million) and before the slope of the backorders change curve starts to decrease (transportation capacity is around 4 million) we should choose our value. For this reason, it is most logical to decide considering the breakpoint in total backorder curve and increase the transportation capacity around 400 times, that is, to make it 4 million.

After all the analysis, we can say that increasing transportation capacity is much more effective than increasing storage capacities. Rather than increasing the storage areas, increasing the number of vehicles and transportation personnel would be a much more logical option for such a sudden outbreak. Our aim should always be to send all purchased vaccines without storing and to use all the vaccines that reach the provinces immediately. In addition, we need z_2 to be greater than or equal to 0.88 in order to reach the herd immunity in all the cities. It is more important for us to provide incentives to increase demand for the first and second dose rather than encouraging the vaccination with booster doses.

CHAPTER V

CONCLUSION

Taking everything into consideration, coronavirus emerged suddenly and affected our lives both psychologically and financially in a negative way. We had to distance ourselves from our loved ones. The fact that we were locked in our homes for such a long time affected us in a negative way. We have become unable to do even the very simple things we used to do. Due to the cases, both the physical and psychological burden of doctors and nurses increased a lot. The fact that people did not leave the house made the shopkeepers unable to work. Too many places have gone bankrupt. Some of us lost their jobs because not many employees were needed. Vaccination is our greatest weapon against this pandemic.

Although we want to get rid of this pandemic as soon as possible, we also have to consider the financial situation of the country. Therefore, instead of buying and stocking a lot of vaccines, we need to make a demand-based purchase. Thus, we would have met the demand and not inflicted more financial damage on our country in these difficult days. With this in mind, we conduct a survey and try to find out what people think about getting vaccinated. We try to make a weekly forecast from this analysis. Then, we create an optimization model, which can be used while planning the vaccine supply chain using our forecasts. We model our problem as a lexicographic optimization, which is a multi-objective optimization method since we have multiple objectives including the minimization of backorders, purchasing, transportation, storage and reaching the herd immunity.

In the analyzes we made using our model, we realize that increasing the transportation capacity is more important than increasing the storage capacities. We try to understand the effects of transportation capacity change on our total backorders, purchasing, transportation cost, storages and reaching the herd immunity.

In addition, we present what percentage of people who had their first dose should have their second dose in order to reach herd immunity in all provinces.

Our aim is to create a methodology that can be used in such a sudden epidemic situation. The government can make a good supply chain plan using these methods and more accurate data. If it is desired to develop this study a little more, a brand preferences index can be added. So that, the purchasing would be made according to the brand preferences. And the model can be solved with more accurate parameters and a data that is collected from a larger population.

APPENDIX A

VACCINE SURVEY

What is your gender?

What is your age?

What is your income level?

What is your education level?

What is your marital status?

What city are you in?

What is your job?

During the pandemic period what is your way of working?

How many people do you have on average in your work environment?

Have you infected with Covid-19 before?

How many people in your family have had Covid-19?

How many existing chronic diseases do you have? (cancer, cardiovascular disease, hypertension, diabetes, etc.)

How many hours a day do you spend outside?

How many people live in your house?

Are you planning to get vaccinated?

7-point Likert-scale questions

If the place where I work recommends that I get vaccinated, I will.

I think the complications of Covid-19 are serious.

I am afraid of catching Covid-19.

I am afraid of infecting others with Covid-19.

The vaccine makes me less likely to get Covid-19 or its complications.

I am concerned about the safety of the Covid-19 vaccine.

I am concerned about the effectiveness of the Covid-19 vaccine.

I am concerned about the side effects of the Covid-19 vaccine.

I will only get the Covid-19 vaccine if the vaccine is administered by many in the public.

I trust the number of cases and deaths that have been announced.

I have previously refused a vaccine for myself or my child because it was recommended by a specialist, but because I found it useless or dangerous.

It is acceptable for governments to force people to get the Covid-19 vaccine.

Restrictions on people who are not vaccinated will/have affected my choice to get vaccinated.

APPENDIX B

WEEKLY FORECAST

Table 8: The weekly forecast for dose 1 and 3

	Dose 1	Dose 3											
Location	Week 1	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12
Adana	235739	16037	11780	17717	26808	79992	42644	145896	35245	107850	62126	42057	48260
Adıyaman	85645	4133	2553	3763	6717	17875	7206	23002	11904	28241	14681	10507	11819
Afyon	85107	7484	4023	5372	10254	24448	16364	37532	12104	38910	26055	15174	13066
Ağrı	69308	3732	3225	3939	6005	9844	7819	12152	7424	24497	15072	9465	10784
Aksaray	56005	3185	1760	2945	4723	11364	6707	20263	5799	22005	12012	7958	8719
Amasya	21745	3546	2689	4181	7524	18113	9119	22085	4997	21864	8477	6123	6199
Ankara	447697	50806	45260	69740	154197	292221	148568	340369	125228	242196	142585	104776	102318
Antalya	176410	25755	18587	25753	43871	116662	82255	154387	61997	123594	78442	51265	57966
Ardahan	7514	885	832	916	1622	3811	1439	5946	992	6336	3694	2942	2260
Artvin	14811	2110	1145	1459	3193	9312	4690	10677	3997	11789	5035	3318	3225
Aydın	74526	13098	10435	14082	26614	59062	39749	71218	20723	59326	30237	20593	20978
Balıkesir	69125	13671	7988	15379	29377	75974	53201	92778	24151	63224	31144	22124	23667
Bartın	17543	2372	1309	1830	3464	10872	6507	16324	5295	9802	5440	3588	3482
Batman	98296	2237	1640	2527	3747	9886	4946	17211	9248	22888	12636	12347	10312
Bayburt	15270	818	538	609	984	2029	1218	4124	1232	4346	1996	1475	1588
Bilecik	18047	2141	1264	2201	5024	12662	6788	17971	3805	10654	4899	3837	4365
Bingöl	49452	1414	1121	1585	2174	4221	2026	9210	6030	14327	6625	4629	6473
Bitlis	55182	1461	875	1072	1659	4028	3093	9481	3927	14153	7195	6247	11686
Bolu	31744	3193	2703	3891	6607	16522	7082	19176	5215	17483	7342	5627	5461
Burdur	21869	2914	2253	3161	5515	12617	7380	17517	5148	18689	7697	5187	5447
Bursa	317425	30980	19171	34134	62508	146205	92835	173907	44958	155706	86141	55743	58514
Çanakkale	23738	5736	4219	8270	15374	38068	24063	35766	11855	28281	12228	9037	11017
Çankırı	26205	2282	1131	2074	3496	7962	5448	11525	2510	10628	4485	2879	3261
Çorum	50961	5459	3809	6478	10005	22458	13182	32202	9354	31568	14566	9493	9980
Denizli	84922	10985	6154	9515	22415	51429	28914	77792	21706	61643	26664	18471	21485
Diyarbakır	310582	6569	4071	8079	11608	29813	18627	47536	20826	69880	38927	26344	34556
Düzce	49547	3445	2043	2855	5166	15164	9307	28344	7493	19556	8785	6008	7315
Edirne	22659	4564	3429	6288	10143	25039	16668	27813	9195	20422	11611	8049	7007
Elazığ	92328	4895	2970	4291	7215	16796	10787	26226	11572	25841	11517	8740	10680
Erzincan	31608	2064	1316	2355	3953	9665	5611	12895	4162	12767	4926	3771	4700
Erzurum	103880	6317	3144	4372	7649	17572	12403	39149	23538	28768	16247	14633	14925
Eskişehir	69801	10042	5508	12129	23651	60149	29038	60791	16621	42075	21128	14891	15815
Gaziantep	209676	11722	8205	10805	22285	52061	26791	88698	26783	100331	64042	44492	42956
Giresun	39835	5350	3193	4495	8340	21086	16922	26981	9883	28244	12588	8455	9770
Gümüşhane	32618	1461	945	1038	1912	3515	1660	6454	2789	6830	3242	2051	2435
Hakkari	26791	1045	808	2012	3154	5803	1759	17587	3702	12983	7495	7230	9526
Hatay	155017	9846	7153	13054	23529	48161	28695	82525	18065	88889	53374	35463	36276
Iğdır	26350	1211	1578	1549	2128	3550	2112	6849	4492	8456	4140	4866	5890
Isparta	39361	5049	3460	5912	10534	20916	10343	25989	6483	26560	10962	7454	8369
İstanbul	1814245	118488	78164	158294	311846	819030	493673	822852	242088	672926	376870	273917	300862
İzmir	331845	41302	28815	54461	114090	270106	165029	277108	87828	217585	111668	76673	81274
Kahramanmaraş	131938	7650	4692	6460	10970	25276	15297	49012	14015	73070	39434	23234	24816
Karabük	31667	2737	1674	2569	4057	10756	7251	15516	4814	11545	5465	4003	4245
Karaman	28277	2077	1239	1821	3862	8647	5254	13909	4179	13914	7590	4878	4819
Kars	35283	1673	1268	2256	3801	6607	3302	14198	5973	16371	7686	5331	5968
Kastamonu	40216	4385	2516	3382	8352	18239	12215	23876	8133	19743	9013	6987	7230
Kayseri	141921	12336	8842	13081	21894	50029	18428	92788	26350	72066	34921	24616	26657
Kırıkkale	34790	4070	2384	2797	4989	9926	4709	15979	5314	14185	6477	4662	5087
Kırklareli	20426	3198	2187	5025	8969	21804	14132	28048	7745	20579	9536	6366	6738
Kırşehir	25602	2410	1438	2621	4666	11087	5934	15230	3578	13453	5611	3945	4531
Kilis	8527	1346	873	1122	2224	3395	1635	6896	1795	8108	4821	3298	3726
Kocaeli	210366	16878	10641	19131	36872	97390	52998	113802	36105	92208	48640	33984	39437
Konya	283669	16736	12229	19858	33501	68599	37796	102468	36341	104811	58076	39365	44567
Kütahya	71894	6165	5428	6894	10000	24995	11854	36221	10297	31213	13956	9589	10512
Malatya	95754	6742	3681	6366	10907	25226	12776	42934	8862	41590	22735	13296	14855
Manisa	118113	12376	9558	15924	32686	67632	42410	76072	28263	100671	40080	24884	28328
Mardin	139856	3421	1874	3108	5518	12573	6001	20820	13133	31419	17249	16606	17966
Mersin	148347	13671	9778	16403	34290	77243	39003	120593	30897	98296	56764	37567	41567
Muğla	-3726	14752	12843	15638	30160	70383	44186	81820	25636	59306	30940	20935	22363
Muş	65685	1253	1012	1543	2854	4403	2643	10089	6565	18021	7824	6332	9401
Nevşehir	34955	3015	1673	3106	6111	13172	6600	16102	4943	15139	9483	5220	5209
Niğde	47725	2639	1590	2944	5749	12216	6941	17818	5018	20940	11484	6350	6335
Ordu	61334	7845	4669	8931	16037	39148	26558	50354	15844	41177	21282	13532	15660
Osmaniye	40899	3725	1994	4086	7014	18024	10271	32665	8769	34990	15066	10810	11862
Rize	34210	3872	2130	3056	5910	14220	8796	20776	5434	19509	11134	7094	7011
Sakarya	131247	10050	5660	8185	15717	44613	29262	56976	17150	45642	24573	18235	19978
Samsun	127892	13064	11483	14178	20142	51933	36739	85895	26094	69003	39234	25803	28556
Siirt	49246	1128	879	1039	2150	4846	3495	7681	8827	13201	8576	6530	7471
Sinop	21143	2627	1769	2312	4598	11078	6850	10857	4880	11660	5590	3878	3985
Sivas	77626	6242	4101	5266	10543	26525	17818	34625	9778	34967	16380	11206	12687
Şanlıurfa	349650	6233	3951	6442	9951	19368	12453	43485	24977	62410	39076	37366	36863
Şırnak	60106	2163	2488	3820	4703	9874	2866	18499	11468	31011	18038	13910	11041
Tekirdağ	66242	9417	6030	10405	20863	61252	40927	69969	35484	54979	34148	23537	23245
Tokat	65700	5703	3207	6080	10043	24829	17452	33793	9229	30361	13925	11211	10907
Trabzon	87433	9488	5949	8968	14211	36103	22550	50736	14860	35157	19600	13975	15697
Tunceli	9137	994	1082	1074	1927	4186	2433	4397	1818	5515	1877	1333	1251
Uşak	33876	3957	2393	3924	6863	16189	9120	27453	8932	18658	9239	6928	6676
Van	138507	5459	5597	7122	9224	19734	14456	38818	12237	64128	37118	22598	25007
Yalova	18919	2514	1519	3742	7340	17371	11843	16382	4285	12437	6922	4866	5858
Yozgat	60828	4064	2146	2740	5207	12838	7802	21849	6246	21839	10207	6881	7876
Zonguldak	59383	6390	3767	6758	12832	28938	19632	38327	10883	29316	12950	9569	11346

Table 9: The weekly forecast for dose 2 and 4

	Dose 2				Dose 4									
Location	Week 1	Week 2	Week 3	Week 4	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12
Adana	61862	57423	57237	55833	23012	40200	15174	3081	24660	11991	22736	24946	18507	15047
Adıyaman	14275	10962	11287	12111	2997	7594	4781	533	4067	2163	4624	4256	3192	3087
Afyon	17064	17235	16884	14522	7976	14746	6925	1693	10724	6784	11419	12200	9099	6628
Ağrı	16916	15934	11978	15583	1200	2387	1536	394	1557	856	2213	2820	1901	1665
Aksaray	13835	12816	11670	9514	3123	5776	3133	638	5324	2630	5362	5269	4028	2885
Amasya	8927	5470	5320	5099	5803	14377	5575	1076	7909	3148	8553	6451	4253	3144
Ankara	114771	119432	113958	101588	110670	143553	45024	12825	80140	51062	70736	70688	51347	38825
Antalya	82717	73706	61670	50514	37165	61281	23798	7175	36504	24157	38451	39443	25432	17974
Ardahan	3387	2861	3276	2031	991	2662	1799	210	2280	610	1890	1690	1479	848
Artvin	5498	4120	3827	3178	2893	6292	3568	756	3860	2501	4177	3591	3147	1940
Aydın	26485	22289	21185	20841	28822	50556	18924	5710	27495	14543	23397	20978	15942	12890
Balıkesir	29682	24722	22345	21584	33133	69418	30282	9078	40397	18689	28997	24376	17809	12877
Bartın	3987	3813	3767	3478	2546	6630	3965	560	4028	2503	3256	3068	2423	1908
Batman	23661	15968	18025	9929	1343	2368	1997	403	2347	1295	3239	3372	2970	1359
Bayburt	2515	1999	1989	1951	468	1554	920	139	1201	818	1476	1353	1061	864
Bilecik	4908	3489	3684	4093	2960	6784	3104	667	4775	2382	3935	2984	2439	1894
Bingöl	13804	7562	6437	5921	945	2162	1284	180	2051	1292	3351	2830	1722	1243
Bitlis	15583	9485	9814	14880	759	1523	864	322	1475	853	1684	1803	1743	1924
Bolu	7113	5104	5479	5479	5449	10380	4200	769	6356	3790	5767	4996	4331	3566
Burdur	8942	6272	5512	4741	5921	12061	5125	885	6664	3718	7294	5776	3620	2524
Bursa	75920	67397	67383	65596	33459	63449	25606	7382	38930	19320	38477	36065	27764	21528
Çanakkale	13312	9943	9384	10996	14954	25528	10528	3498	14730	9520	13970	11431	8100	6632
Çankırı	4660	3610	3181	3077	3512	7656	3526	938	5524	2864	4890	4029	2930	2321
Çorum	14169	10218	9762	9030	6348	14333	7030	1499	10129	5710	10851	9235	7150	5054
Denizli	27665	20783	19680	21377	13587	27000	11848	2098	18114	10587	17234	14948	10948	9187
Diyarbakır	73892	47694	37757	31608	6140	9649	5824	1756	8664	4311	12266	10306	6797	5189
Düzce	9478	6894	6448	7524	4151	8078	3652	676	6281	3762	5082	4333	3037	2663
Edirne	9541	8889	7047	5920	10861	19143	7832	2328	12246	7649	10285	9832	6084	4475
Elazığ	18619	13013	12661	12415	4792	9310	4488	1190	6976	4549	8230	7035	5582	4298
Erzincan	6574	4685	4638	5108	2819	6940	3736	868	4797	2505	4856	3838	3014	2117
Erzurum	21986	16418	16104	14874	4192	10442	5730	1599	9230	7736	8410	7811	6481	4909
Eskişehir	17250	16278	16103	15793	20551	31859	11156	2698	17700	9821	14919	13676	10020	7637
Gaziantep	56483	59563	62654	61844	10059	17806	7447	1290	12754	5979	13033	13994	11123	9879
Giresun	13457	9231	8073	8240	8645	18744	10166	2640	11907	7870	11883	8919	5879	5283
Gümüşhane	4366	3324	3152	3019	1110	3462	1836	257	2537	2095	3805	2942	2045	1442
Hakkari	3767	2783	2836	3322	433	720	523	86	705	382	473	920	775	807
Hatay	50882	47807	49813	44599	11179	21982	8917	1824	12132	3886	13599	17687	14121	11132
Iğdır	6490	4733	8303	7925	585	1614	862	204	1238	1010	1320	1252	1664	1219
Isparta	13443	9797	8991	8199	8997	15532	6965	1250	9360	4716	10767	9618	6997	4835
İstanbul	365625	324576	320044	320054	199429	250405	80375	30199	145461	77582	128350	116774	87056	71647
İzmir	100989	89560	83327	79883	93083	156648	53493	15610	71086	42843	71660	66071	47630	35829
Kahramanmaraş	36179	34253	33032	35858	6409	15458	7288	1410	9808	5021	12325	13903	9510	8128
Karabük	5390	4345	4857	5163	2747	6606	3501	886	4728	2907	3969	3936	3046	2452
Karaman	8150	6418	6291	5507	2317	5783	3194	541	4150	2399	4368	4136	2906	2060
Kars	8955	6578	6074	5320	1861	3796	1928	301	2909	1513	2878	2542	2262	1534
Kastamonu	9169	6999	7462	7675	6128	13378	7077	1806	9733	6334	8432	7485	6878	5163
Kayseri	38044	33211	34409	32725	14674	28644	11976	1587	18585	12139	19146	18586	14302	10944
Kırıkkale	7112	5561	5413	4586	3565	7810	3303	599	4354	3095	4548	4340	3296	2356
Kırklareli	7838	6465	6205	5948	6732	15047	5506	1483	8768	4723	7574	6637	5010	3658
Kırşehir	6585	4520	4719	4431	4276	7272	3393	658	5425	2366	5007	3889	3112	2275
Kilis	5855	4572	4855	4873	822	1399	646	130	1177	471	1168	1315	1310	1125
Kocaeli	49237	40655	41918	44150	21246	35592	13972	3611	22650	12599	20384	18182	13563	12035
Konya	69607	60711	55824	50566	21515	41322	21156	3935	30100	18455	32648	30302	22849	16409
Kütahya	15067	11737	10957	10650	5383	13046	6721	1097	11171	6445	10316	9539	8287	5876
Malatya	24397	22617	18269	16891	9258	17814	7898	1406	11451	4998	12708	12255	7966	6556
Manisa	44843	31515	28816	31625	17437	35116	16041	3030	17904	14982	25436	22554	15480	10973
Mardin	30898	24723	33997	25493	1735	3535	1931	401	2314	1739	3794	4377	4288	2819
Mersin	56219	51715	48658	42659	28268	51481	19520	3711	27955	13734	26720	28606	20259	14766
Muğla	25957	23639	22361	21389	31194	50288	19185	5833	27717	14059	20761	18478	12952	10803
Muş	15789	11418	10159	11218	835	2300	978	265	1557	1056	2469	2071	1733	1628
Nevşehir	7781	7799	6584	5694	4315	8200	3461	761	3989	2259	5084	4828	3078	1943
Niğde	11874	10537	8359	6962	4142	8428	3964	945	5707	3591	6166	6381	3965	2542
Ordu	18790	14304	12502	13477	11960	25471	12995	3103	15637	9875	13822	11497	8597	6892
Osmaniye	19260	12910	13079	11274	5099	11352	5355	937	7119	3973	8689	6971	4723	3813
Rize	11112	10566	10044	7794	5571	10447	4629	892	6937	3694	7396	7884	5969	3762
Sakarya	27652	22150	22561	21940	10422	20621	9465	2625	13924	8483	14574	13431	10749	8190
Samsun	37604	32227	28427	26807	20454	32608	14600	3782	23274	13396	22249	20517	15543	12823
Siirt	16581	9059	5680	4461	539	1220	922	300	1262	1218	1449	1471	844	595
Sinop	4895	4083	3971	3898	4228	8496	4264	1104	5176	3865	5238	4680	3847	3084
Sivas	17537	13888	13669	14354	9017	19644	10214	2283	11672	6537	12281	11003	9103	6295
Şanlıurfa	63354	52830	61298	48024	3266	5990	3118	676	5507	3123	6810	7345	7048	4874
Şırnak	17707	14307	14917	10615	733	1147	1069	130	916	693	1655	1993	2038	1431
Tekirdağ	25557	25790	24307	21813	15608	32085	11742	3645	16811	11930	15526	15294	10769	7887
Tokat	16180	12120	11692	10376	8106	18045	8622	2243	11801	5908	12072	9591	7976	5838
Trabzon	19438	18119	18455	18393	13274	23437	11208	2749	16333	8474	12680	12513	9753	8678
Tunceli	2277	1266	1281	1102	1493	3672	1872	430	1790	1080	1935	1601	1053	798
Uşak	8337	6847	7162	6700	4040	9759	4200	786	7016	4337	5319	5719	4506	3545
Van	40594	32851	24816	24174	2960	5732	3413	1198	4717	1616	6370	6172	4141	2888
Yalova	7459	6102	6171	5964	8609	11612	4128	1631	6622	3367	5554	4036	3336	2305
Yozgat	12419	9100	8953	8616	3700	8657	4575	867	6578	4027	8703	7091	5858	4593
Zonguldak	13389	10141	10428	11793	8095	15158	7332	2062	10353	6050	10647	8398	7491	6178

APPENDIX C

PARAMETER CALCULATIONS

Table 10: Storage cost, transportation cost, population over 18 and priorities

City	Number of hospital	18+ population	Population per hospital	Storage cost	Transportation cost	2+ dose	Vaccination	Priority
Adana	32	1634068	51064	4	480	984754	0.6026	2
Adıyaman	12	428688	35724	3	804	219224	0.5114	1
Afyonkarahisar	22	555138	25233	2	259	344129	0.6199	2
Ağrı	10	327995	32799	2	1050	154037	0.4696	1
Aksaray	10	305773	30577	2	347	169087	0.553	2
Amasya	7	265500	37928	3	0	199752	0.7524	4
Ankara	83	4343605	52332	4	544	3010013	0.693	3
Antalya	47	1937428	41221	3	953	1352643	0.6982	3
Ardahan	3	73202	24400	1	597	49836	0.6808	3
Artvin	8	137917	17239	1	606	101511	0.736	3
Aydın	24	880654	36693	3	313	665964	0.7562	4
Balıkesir	25	1006094	40243	3	884	801429	0.7966	4
Bartın	3	161614	53871	4	1075	117638	0.7279	3
Batman	12	388330	32360	2	185	158720	0.4087	1
Bayburt	1	63137	63137	4	420	33475	0.5302	1
Bilecik	8	171721	21465	1	479	123403	0.7186	3
Bingöl	8	197462	24682	1	733	90999	0.4608	1
Bitlis	8	223764	27970	2	134	90538	0.4046	1
Bolu	11	251305	22845	1	237	172856	0.6878	3
Burdur	9	215502	23944	1	478	158107	0.7337	3
Bursa	42	2355561	56084	4	877	1488360	0.6318	2
Çanakkale	14	443462	31675	2	686	360758	0.8135	4
Çankırı	9	153648	17072	1	746	101611	0.6613	3
Çorum	16	414919	25932	2	683	285821	0.6889	3
Denizli	23	807316	35100	3	871	562316	0.6965	3
Diyarbakır	27	1133960	41998	3	233	455773	0.4019	1
Düzce	8	303461	37932	3	698	187263	0.6171	2
Edirne	11	338138	30739	2	599	269617	0.7974	4
Elazığ	11	441549	40140	3	759	239763	0.543	1
Erzincan	10	183133	18313	1	1381	115710	0.6318	2
Erzurum	23	539502	23456	1	650	293262	0.5436	1
Eskişehir	15	709144	47276	4	423	519090	0.732	3
Gaziantep	31	1354737	43701	3	493	703324	0.5192	1
Giresun	17	365129	21478	1	447	275583	0.7548	4
Gümüşhane	6	112772	18795	1	585	57789	0.5124	1
Hakkari	4	187788	46947	4	1071	89537	0.4768	1
Hatay	25	1148606	45944	4	240	667034	0.5807	2
Iğdır	4	134865	33716	2	315	67574	0.501	1
Isparta	15	347657	23177	1	661	245464	0.7061	3
İstanbul	235	11727713	49905	4	181	7020663	0.5986	2
İzmir	60	3480351	58005	4	344	2500364	0.7184	3
Kahramanmaraş	18	806323	44795	3	262	441404	0.5474	1
Karabük	6	198010	33001	2	312	129593	0.6545	3
Karaman	7	191716	27388	2	647	119653	0.6241	2
Kars	8	199252	24906	1	561	112329	0.5638	2
Kastamonu	18	307120	17062	1	569	219948	0.7162	3
Kayseri	27	1038272	38454	3	1022	644728	0.621	2
Kırıkkale	7	218781	31254	2	618	137561	0.6288	2
Kırklareli	10	297972	29797	2	994	231062	0.7754	4
Kırşehir	5	188447	37689	3	274	127435	0.6762	3
Kilis	2	96877	48438	4	342	57262	0.5911	2
Kocaeli	28	1480717	52882	4	554	910088	0.6146	2
Konya	45	1645982	36577	3	808	940426	0.5713	2
Kütahya	13	461744	35518	3	311	295778	0.6406	2
Malatya	18	598069	33226	2	404	354355	0.5925	2
Manisa	29	1119617	38607	3	1057	755444	0.6747	3
Mardin	12	534604	44550	3	423	204974	0.3834	1
Mersin	27	1384547	51279	4	436	920925	0.6651	3
Muğla	21	798552	38026	3	590	698978	0.8753	4
Muş	7	253685	36240	3	376	102748	0.405	1
Nevşehir	10	233063	23306	1	730	147107	0.6312	2
Niğde	8	266555	33319	2	809	158847	0.5959	2
Ordu	17	599720	35277	3	838	443132	0.7389	3
Osmaniye	10	387038	38703	3	369	254449	0.6574	3
Rize	11	273296	24845	1	1209	184482	0.675	3
Sakarya	19	791629	41664	3	213	473769	0.5985	2
Samsun	26	1049281	40356	3	262	703709	0.6707	3
Siirt	9	204381	22709	1	226	86246	0.422	1
Sinop	7	175415	25059	2	774	129500	0.7382	3
Sivas	20	487964	24398	1	371	311419	0.6382	2
Şanlıurfa	19	1200571	63187	4	76	416845	0.3472	1
Şırnak	7	318955	45565	4	971	153689	0.4819	1
Tekirdağ	19	823690	43352	3	1191	593136	0.7201	3
Tokat	15	465887	31059	2	290	310188	0.6658	3
Trabzon	21	632618	30124	2	1091	426216	0.6737	3
Tunceli	6	69643	11607	1	1157	50221	0.7211	3
Uşak	8	290914	36364	3	418	198318	0.6817	3
Van	14	717646	51260	4	220	353347	0.4924	1
Yalova	7	214291	30613	2	715	159888	0.7461	3
Yozgat	16	321259	20078	1	571	189267	0.5891	2
Zonguldak	12	474011	39500	3	236	325018	0.6857	3

APPENDIX D

PRIORITIZING OBJECTIVES

Table 11: The optimal values for the objectives

Objective Functions	Backorders First	Herd Immunity First
Herd immunity unsatisfaction	5.48688537	3.18429088
Number of non-immune cities	47	28
Backorder for dose 1 priority 1	95,959,760	106,771,655
Backorder for dose 1 priority 2	224,660,176	224,660,176
Backorder for dose 1 priority 3	104,833,768	104,833,768
Backorder for dose 1 priority 4	14,147,120	14,147,120
Backorder for dose 2 priority 1	94,003,522	75,598,667
Backorder for dose 2 priority 2	180,742,006	179,303,232
Backorder for dose 2 priority 3	107,587,794	107,587,794
Backorder for dose 2 priority 4	22,670,229	22,670,229
Backorder for dose 3 priority 1	138,806,781	144,635,023
Backorder for dose 3 priority 2	515,410,819	515,533,987
Backorder for dose 3 priority 3	376,757,333	376,757,333
Backorder for dose 3 priority 4	93,312,663	93,312,663
Backorder for dose 4 priority 1	31,225,645	31,225,645
Backorder for dose 4 priority 2	167,986,832	167,986,832
Backorder for dose 4 priority 3	158,162,837	158,162,837
Backorder for dose 4 priority 4	52,900,560	52,900,560
Backorder for dose 5 priority 1	0	0
Backorder for dose 5 priority 2	0	0
Backorder for dose 5 priority 3	0	0
Backorder for dose 5 priority 4	0	0
Total backorder	2,283,208,090	2,376,087,522
Purchasing	52	52
Transportation cost	336,206,468	423,551,824
Storage cost of locations	0	0
Storage of central depot	0	0

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