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How to Determine the Optimal Number of Cardiologists in a Region?

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Abstract: This paper proposes an approach to determining the optimal number of medical specialists in a particular territory. According to the author's theoretical model, in order to maximise public welfare, the marginal contribution of the last physician recruited to the growth of the public utility function should be equal to the marginal cost of attracting them and providing conditions for their work. To empirically assess the contribution of physicians to the number of lives saved, the CVD mortality rate is modelled using the instrumental variable method. At the level of provision of cardiologists in the amount of 1 per 100,000 people, their marginal contribution to the number of lives saved is not less than 124 per 100,000 people, with a further decrease of 10 per 100,000 people with an increase in the level of provision of one unit. The use of the obtained results will increase the validity of managerial decisions and improve the determination of the optimal number of doctors when choosing between alternative possibilities of spending money on hiring doctors with different profiles or other expenses, especially in the case of limited resources.

Keywords: health-care markets; cardiovascular mortality; health-care workforce; applied microeconometrics; spatial econometrics; instrumental variable method; quasi-public goods

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1. Introduction

The present study attempts mathematical modeling and proposals of empirical applications based on the theory of public goods and methods of applied econometrics in industrial organisation in the field of health care. In many countries of the world, the state takes an active part in the formation and regulation of the market of health services [1]. For example, the state can guarantee its citizens access to the majority of the most common services in the sphere of complex health care on the basis of the application of the mechanism of compulsory health insurance [2]. In Russia, authorities at the regional and federal levels are faced with the need to make decisions regarding the provision of medical services. This concerns decisions related to the determination of the numbers of specialist doctors, medical staff, and beds, and decisions in the field of personnel training, including the planning of the number of budgetary places in specialist educational institutions. But what is the basis for making decisions about the optimal number of doctors, such as cardiologists, at the level of a particular region? To date, such decisions are made on the basis of federal regulations, which contain standardised average coefficients that determine the number of doctors per 100,000 people, taking into account the expected number of requests for medical services and the average appointment times [3]. These coefficients do not sufficiently take into account the specific characteristics of territories, such as socio-economic and demographic characteristics, geography, and other parameters, when assessing the demand for specialist professionals [4,5]. For example, according to Rosstat data, in the Penza region in Russia, the mortality rate from cardiovascular diseases was 749 per 100,000 people, with

a cardiologist-supply rate of 12.4 per 100,000 people, while in the Nenets Autonomous District, the corresponding mortality rate was less than 348 per 100,000 people, with a cardiologist-supply rate of 6.8 per 100,000 people in 2019 [6].

At the theoretical level, the research problem is defined by the existence of a gap that arises when trying to answer the question of what should be the optimal equilibrium volume of medical services in order to maximise the indicator of public welfare. The existence of this gap is due to the fact that the state-guaranteed access to free health services in some cases leads to the full or partial characterisation of these services by the properties of public goods [7]. The state can strive for universal free access to health care because the consumption of health-care services is a source of positive externalities, and, thus, without state guarantees or other forms of regulation, such as subsidising health-care services, underconsumption of health-care services compared to the optimal level can be expected [8]. On the other hand, the fact that health-care services begin to be characterised by the properties of public goods leads to other well-known problems, such as the problem of the stowaway, which creates the preconditions for the underfunding of the health-care sector through the mechanism of compulsory health insurance [9].

This study presents a theoretical framework for ascertaining the optimal quantity of cardiologists by employing Samuelson's equation [10]. However, in order to apply this framework in practice, it will be necessary to estimate the utility of hiring additional physicians in monetary terms, in order to compare it with the corresponding costs. This estimation of the utility in monetary terms would require, on the one hand, an estimate of the cost of living, which in turn can take into account both an estimate assuming that all other factors are equal and an estimate taking into account life expectancy and life quality [11]. On the other hand, it is necessary to calculate the impact of the number of specialist physicians on the mortality rates from respective diseases [12]. This is the main focus of this paper.

This study is structured as follows. In the "Introduction" section, the research problem is presented and the relevance of the work is outlined. In the section entitled "Hypothesis development", the research question and the main hypotheses are formulated. The "Literature Review" section summarises the key findings in the literature on the research question under consideration. The "Theoretical model" section provides a description of the author's theoretical model to answer the question of the optimal supply of health-care services. The "Data and methods" section presents the data and methods used in this paper to empirically implement the proposed theoretical model. The "Results" section describes the main measures obtained from the econometric modeling with the regression equations. In the "Discussion" section, the main results are discussed and compared with those already known in the literature. In the "Conclusion" section, the main findings are presented, the theoretical and practical significance of the study is assessed, and the directions for further research are outlined.

2. Hypotheses Development

Research question: How will the level of mortality from cardiovascular disease change, all other factors being equal, if the indicator characterising the level of availability of cardiologists increases?

Hypothesis 1. *The negative impact of the indicator characterising the level of availability of cardiologists on the mortality rate from cardiovascular diseases may be underestimated when using econometric modelling without the use of quasi-experimental methods due to the presence of false negatives and false positives between these indicators.*

Hypothesis 2. *The additional reduction in CVD mortality due to the recruitment of an additional cardiologist will decrease as the indicator of cardiologist availability increases.*

The negative effect of the specialist-supply indicator on mortality in certain disease areas is well documented in the literature [13]. This impact can be explained by a significant reduction in patients' waiting times in queues, which, in turn, can contribute to the receipt of timely medical care [14]. Timely medical care is also important in the context of the presence of expected transaction costs in the perception of potential patients, which has a significant impact on their decisions as to whether to seek medical care. For example, if a patient believes there are lengthy waiting lists and other transaction costs due to staff shortages, he or she might be more inclined to delay their hospital visit. All other factors being equal, this delay increases the likelihood of an adverse outcome [15]. Professional rivalry amongst specialists might also be noteworthy. In situations characterised by an acute dearth of physicians with relevant expertise, there may be diminished motivation for them to allocate resources or strive to enhance the calibre of their practice. This can be illustrated by a reduced inclination to attend courses to augment their qualifications. Such scenarios arise largely because, under prevailing circumstances, employers possess a pronounced incentive to retain these practitioners, regardless of conditions.

In addition to the above-mentioned channels of influence of the level of medical-personnel supply on the population mortality from the corresponding disease areas, it is important to emphasise the existence of conditions for the emergence of false positives and false negatives, which may lead to the underestimation or overestimation of the corresponding influence and, to a certain extent, prevent the interpretation of causal relationships.

False positives can occur for a variety of reasons, but they usually fall into one of the following categories: the presence of reverse causality, omitted variables, and peculiarities in the statistics used. In our case, the problem of reverse causality seems to be significant. There may be a spurious correlation between the availability of medical personnel and mortality rates, as other factors can drive mortality rates. For instance, certain regions may have high mortality rates due to cardiovascular diseases, which could be associated with a high proportion of elderly people. Moreover, it is conceivable that the authorities may aim to boost the number of specialist medical personnel in areas with prevalent disease-related mortality rates. However, calculating the correlation between mortality variables and the availability of doctors may yield a positive correlation in such cases. The data would show that where there were more doctors, mortality would be higher. It would be clear that doctors were not the cause of high mortality in such cases. However, unfortunately, in econometric modelling, if this fact is not taken into account, the true effect of doctors on mortality can be underestimated, and sometimes, counterintuitive results can be obtained [16].

At the same time, even if a negative impact is detected during modelling, there is always a risk that this impact is underestimated due to the fact that reverse causality may exist. The underestimation of the corresponding negative impact can also lead to the problem of missing variables, such as the variable characterising the level of well-being and lifestyle of the inhabitants of a given area [17]. For example, it is known that a high income can lead to a person having a less physically active lifestyle, making them more susceptible to the influence of bad habits, sleep disorders, and being obese [18]. On the other hand, high income and the associated level of development of a given area will contribute to a higher indicator of availability of medical personnel in that area [19]. In combination, this will result in areas with both high mortality rates and high physician availability, creating a false-positive relationship.

Existing inaccuracies in the statistical data may also lead to the underestimation of the negative impact of physicians on mortality. This may be due to the fact that, in reality, the true level of incidence or mortality of a disease is not observed, but only the rates of detected morbidity or mortality. Thus, the availability of specialist physicians in an area has a greater direct effect on the recorded morbidity rate and a lesser effect on the recorded mortality rate. Therefore, it may be expected that areas characterised by a high availability of specialist physicians will be characterised by a higher level of recorded mortality from specific diseases [20]. On the other hand, the high availability of specialists may, in some

cases, be associated with false diagnoses, which may also contribute to an increase in detected morbidity and mortality in particular areas.

False negatives may also be associated with omitted variables. For example, in practice, it is quite difficult to assess factors related to cultural aspects that characterise the attitude of the inhabitants of a given territory towards their health at the regional level. At the same time, an attentive attitude of the inhabitants of a region to their own health can make them more likely to lead a healthy lifestyle, such as by, to eating properly, leading a physically active life, which will contribute to a reduction in the indicator characterising the mortality rate of a specific illness [21]. At the same time, people who pay attention to their own health can also pay attention to issues related to the prevention of certain diseases, such as through early visits to doctors, which will also contribute to an increase in the demand for medical services in the territory and create favorable conditions that contribute to the increase in the number of medical personnel [22].

As a result, there are areas with both low mortality and a high availability of specialists, but the primary cause is not the doctors themselves, but instead, the attitude of the population to its own health. Similar reasoning can be given when analysing the influence of the parameter of the level of medical literacy of the population, which cannot always be expressed as an indicator of the level of education in general [23]. The indicator of the level of development of the territory can also act as a missing variable. On the one hand, a more developed territory is more likely to have high rates of availability of specialist doctors, while it is important to note that it is also more likely to have lower mortality rates due, for example, to preventive measures, such as popularisation of sports, access to quality food, medicines, and opportunities to spend leisure time and organise quality recreation [22]. These circumstances may also contribute to inaccurate estimates in the absence of relevant data.

Each additional doctor offers additional benefits, but the magnitude of these benefits decreases. Even if the amount of equipment and other infrastructure also increases, it may be that the doctors will initially help patients with simpler diagnoses and treat an increasing number of severe cases, so that each new doctor will face more difficulties and, consequently, the contribution of each additional doctor to the saving of lives will decrease over time, although it will remain positive.

This study contributes to the theoretical research that discusses approaches to determining the optimal level of service provision in quasi-public goods markets using the example of the market for health-care services [24,25]. It also contributes to the literature in the direction of refining empirical methods for assessing the contribution of health-care-financing policies to reducing population mortality, using cardiovascular disease as an example [26].

3. Literature Review

3.1. Health Services as Quasi-Public Goods

The debate about whether health care is a public or private good is still open. Fisk addresses this controversy in an article [27]. If health care is viewed as a commodity distributed by the market, then it is a private good. If health care is considered a public good, then its distribution requires a broadly consensual policy. The author believes that a healthy society can only be achieved through health care based on the principle of solidarity.

This view is shared by Carsten [24], who argues that health care cannot be sold in the same way as health insurance. At the same time, the author notes the existence of market failures due to the inability of some people to obtain health care at the right time or when they need it most. In such cases, the market fails to provide the optimal amount of supply, leading to externalities. The author points out that this problem can be solved by providing universal financial access to health care through insurance or mandatory employer contributions, as well as public benefits and subsidies.

Anamoli, on the other hand, argues that public health care should be concerned only with the provision of public health services, which clearly separates it from private health

care [28]. However, in another paper [25], the author extends Anamoli's concept and argues that attention should also be paid to water purification and air-pollution control. Dees shares this view and believes that only the state can provide clean water and air, as well as guaranteeing wide access to health services [29]. It can be seen that the authors do not come to a clear answer about what public health should be. Moreover, pure public health does not currently exist. The boundaries between public and private goods differ depending on the chosen model of health care. In this case, public health can be considered a quasi-public good.

3.2. Factors Influencing Mortality from Cardiovascular Disease

3.2.1. Risk Factors for Cardiovascular Mortality from Comorbidities

Hypertension is one of the major causes of cardiovascular disease and is increasing worldwide. One study [30] investigated the causal relationship between blood pressure and cardiovascular disease. The authors used Mendelian randomisation, which uses measured gene variability to examine causality as an instrumental variable. Positive associations were found for all cardiovascular diseases, supporting the findings that the lower the blood pressure, the lower the risk of cardiovascular disease. In another study [31], the authors used the Cox model to assess the risks of increased systolic and diastolic blood pressure, as well as heart rate, on the manifestations of cardiovascular disease. It was found that elevated systolic blood pressure had a large effect on angina pectoris, myocardial infarction, and peripheral arterial disease, and that elevated diastolic blood pressure had a large effect on abdominal aortic aneurysm. Elevated heart rate was more closely associated with peripheral arterial disease.

Multiple studies show that obesity is associated with cardiovascular disease. Nordestgaard et al. [32] tested the association between body-mass index and the risk of coronary heart disease. The authors hypothesised that control variables such as smoking, alcohol consumption, education, annual income, blood pressure, gender, and age might disrupt the association between dependent and key factors. To address this problem, they used the instrumental-variables method. The results showed that every 4 kg/m^2 increase in BMI increased the risk of coronary heart disease by 26%, and the instrumental variables method revealed a 52% increase in risk. A study by Larsson et al. used the Mendelian randomisation method to assess the association between body-mass index and 14 cardiovascular diseases. Data from the UK Biobank from 2006 to 2010 were used for the study. The sample included about 500,000 adults aged 40–69 years. The results of the study showed that high BMI is associated with an increased risk of aortic valve stenosis and most other cardiovascular diseases [33].

Studies suggest that type 2 diabetes may have a significant impact on cardiovascular disease morbidity and mortality. In one article [34], the relative risk of cardiovascular disease was twice as high in men and three times as high in women with diabetes compared to those without diabetes. In another study [35], estimates from a proportional hazards regression analysis showed that the risk of death from cardiovascular disease was higher in men with diabetes than in men without diabetes, when adjusting for various control factors.

3.2.2. Risk Factors for Cardiovascular Mortality from Unhealthy Habits

Smoking is also an important risk factor. For example, smoking a single cigarette dramatically and temporarily increases blood pressure by activating the sympathetic nervous system. Exposure to tobacco smoke increases the risk of coronary-plaque rupture and causes coronary-artery spasm. A non-linear relationship between daily cigarette smoking and coronary heart disease has also been observed. In addition, there is no evidence that other tobacco products are safer than conventional cigarettes [36].

A meta-analysis [37] summarised the results of the association between alcohol consumption and the risk of heart failure. A moderate inverse association was observed between low alcohol intake and the risk of heart failure. In addition, the results of the meta-analysis showed that previous alcohol consumption was associated with an increased

risk of heart failure. The authors of [38] performed a systematic review of the literature on the use of Mendelian randomisation to identify causal relationships. Due to the heterogeneous application of the method in the reviewed studies, it is not yet possible to draw conclusions about the causal role of moderate alcohol consumption. However, excessive alcohol consumption is a known factor in mortality and the burden of cardiovascular disease [39].

3.2.3. Socio-Economic Risk Factors for Mortality from Cardiovascular Diseases

There is an association between low education, low income, and increased risk of heart and vascular disease. For example, a study [40] examined the effect of income and education on mortality from acute myocardial infarction. The study used the Cox proportional hazards model, adjusting the data for sex, age, marital status, and other factors. The mortality rate in the first 30 days after hospitalisation was 7% among patients aged 30–64 years and 15.9% among patients aged 65–74 years. After 30 days of hospitalisation, the mortality rates were 9.9% and 28.3%, respectively. The adjusted relative risks of mortality in the first 30 and subsequent days of hospitalisation in young low-income versus high-income patients were 1.54 and 1.65, respectively. The situation was similar for education, with rates of 1.24% and 1.33%, respectively. In elderly patients, the adjusted relative risks of mortality in low-income versus high-income patients were 1.27% and 1.38%, respectively. Meanwhile, elderly patients with high and low levels of education did not differ in terms of mortality.

Ho et al. evaluated the association between education level and the risk of acute myocardial infarction [41]. The authors used a Cox model to assess the association between education and outcomes in the study. They also adjusted for demographic factors to test for changes in the association between education and outcomes. In the unadjusted analysis, they found that low education was associated with a higher risk of cardiovascular problems over the course of a year. However, after adjusting for risk, the association between education and death was statistically insignificant. Nevertheless, the risk of developing cardiovascular problems remained significantly higher in the group of people with low levels of education. Hamad et al. conducted an experiment to test how education affects various aspects of cardiovascular disease and associated risk factors. They used the instrumental variables method to determine the effect of education because there was doubt as to whether education was the real cause of cardiovascular disease or whether it was correlated due to reverse causality. The instrument chosen to measure education was the School Education Act. The authors also used fixed-effects models. The results from the instrumental-variables method showed that increased education was associated with reductions in smoking, depression, triglyceride levels, heart disease, and improved HDL cholesterol levels. However, increased education was also associated with increases in body-mass index and total cholesterol levels. When fixed effects were accounted for in the model, these factors became statistically insignificant [42].

The authors of [43] examined the effect of marital status on outcomes in patients with coronary heart disease and at high risk of developing this disease. They used Cox proportional hazards regression to determine the relationship between marital status and outcomes, adjusting for sex, race, diagnosis of arterial hypertension, diabetes mellitus, body-mass index, smoking history, education, employment status, and other factors. There were 1085 deaths from all causes, including 688 from cardiovascular disease and 272 from myocardial infarction. Unmarried people had a higher risk of all-cause death (1.24), cardiovascular disease (1.45), and myocardial infarction (1.52) compared with married people. A similar situation was seen in divorced (1.41) and widowed (1.71) patients. The authors note that the results remained significant after adjusting for medications and other socioeconomic factors.

Gallo et al. used 10-year-follow-up data to estimate the effect of job loss among people over age 50 on subsequent risk of myocardial infarction and stroke. The key variable was a binary measure of involuntary job loss due to business closure, plant closure, or layoff.

Socio-demographic status, economic variables, and comorbidities were used as control variables. Using Cox proportional hazards regression, the authors found that the risk of myocardial infarction and stroke was twice as high among those who lost their jobs involuntarily compared with those who were employed. For many people, job loss is an extremely stressful situation that can trigger cardiovascular disease [44].

The results of the study showed that there is a causal relationship between anxiety, depression, and acute myocardial infarction and sudden cardiac death [45]. On the other hand, positive psychological aspects such as optimism have been identified as contributing factors to cardiovascular health [46].

Studies [47,48] have found a positive association between air pollution and cardiovascular mortality. Extreme heat and cold have also been found to influence the risk of cardiovascular disease [49,50]. Sex, age, and race differences, low physical activity, and urbanisation are also considered significant factors influencing cardiovascular disease mortality and morbidity in the literature [51–55].

3.3. Econometric Issues in Assessing the Influence of Physicians on Cardiovascular Disease Mortality Rates

A number of studies have been conducted in the scientific literature on the impact of the number of physicians on cardiovascular disease mortality [56–58]. Simionescu et al. related the number of deaths from cardiovascular disease to per capita health-care expenditure, the number of public hospitals with cardiology departments, and the number of cardiologists [56]. The authors used Bayesian linear-regression models for time series at the national level and panel-data models with fixed effects at the regional level to control for unobserved variables. The Bayesian model showed a negative effect on the number of deaths, and an increase in the number of physicians and hospitals was associated with an increase in mortality. The fixed-effects model showed that, on average, an increase of one cardiologist reduced mortality by one. However, an increase in the number of public hospitals was positively associated with mortality. The authors conclude that the results differ at the national and regional level because of the influence of the number of cardiologists.

Another study examined the relationship between access to health care and preventable mortality from several diseases, including cardiovascular disease [57]. The authors used three models: a pooling model, a fixed-effects model, and a random-effects model. The random-effects model was the appropriate model for estimating the variables related to mortality in men. The researchers note that increasing the number of pediatricians in the region by one would increase the regional mortality rate by 3885 deaths per 100,000 members of the population. The situation is similar for general practitioners (1482). The other two statistically significant variables (the number of pharmacies and number of specialists) have negative relationships, with coefficient values of 3.904 and 0.3777, respectively. For women, the random-effects model was appropriate. An increase in the number of general practitioners and dentists would increase the mortality rate by 0.724 and 0.557 per 100 thousand population, respectively. The numbers of gynecologists, pharmacists, and specialists have negative estimated coefficients. These contradictory results are due to two econometric problems: the omitted-variable problem and the reverse-causality problem. While the authors partially solved the omitted-variable problem by using fixed- and random-effects models, the reverse-causality problem is still important for analysing the relationship between the number of physicians and mortality. It is possible that regions with higher mortality have more physicians not because their presence leads to lower mortality, but because there is a greater need for medical personnel due to high morbidity and mortality. This problem can be partially addressed using instrumental-variables techniques.

One study [58] evaluated the impact of different medical services on hospital admissions. One of the factors was physician density. The authors solved the problem of omitted (unobserved) variables by using spatial autoregressive analysis. In addition, the authors used the instrumental-variables method to solve the problems of omitted variables and

reverse causality. The authors used the medical student factor as an instrument, reasoning that most graduates stay and work in the region where they studied after graduation.

Sundmacher et al. examined the effect of regional differences in the provision of health services on the types of preventable cancer death [59]. The dependent variable was the age-standardised non-negative mortality rate. The reason for using the instrumental-variables method was that the distribution of physicians was not strictly regulated until 1993. There may have been incentives for physicians to move to areas with high and low incidence rates of these cancers, resulting in reverse causality. In addition, there are omitted variables that correlate with both the incidence of mortality from preventable cancers and the supply of physicians. In Germany, individuals who refuse military service can choose to serve in the national system. Most of these positions are in the health sector, so the total number of such positions per 100,000 population was used as an instrument. The results showed that an additional 10 physicians would reduce the incidence of acute cancer by about one case every five years.

A study [60] examined the existence of physician-induced demand for hypertension services in Ghana. A positive correlation between these indicators would have indicated an artificial demand for these services, so the authors assumed the existence of endogeneity. The authors use district population size and male population ratio as instruments, which only affect the demand for health services through the ratio of doctors to the population. A high male population ratio indicated the presence of mining and cocoa farming. This, in turn, indicated a vibrant local economy and high purchasing power. The population of the district indicated a high availability of amenities such as good schools for the children of doctors, the stable supply of electricity and water, and the presence of high levels of economic activity. In addition to the instrumental-variables method, the authors used a fixed-effects model. The results suggest that a 1% increase in physician density increases visitation by 0.75%. This supports the authors' hypothesis that there is an artificial demand for health services in Ghana.

Other researchers examined the effect of physician density on infant mortality [61]. The authors noted the presence of endogeneity problems due to omitted variables and reverse causality. To address these issues, the authors used the instrumental-variables method. The authors used lagged physician density as the instrument. The results of the study showed that an increase of one physician per 1000 population reduces infant mortality by 15% over five years and by 45% in the long term.

4. Theoretical Model

4.1. Need for Government Intervention

The consumption of health services by the population leads to positive externalities. For example, healthier individuals are more likely to be more productive, start new businesses, make scientific discoveries, and achieve other successes that benefit the rest of society [62]. The presence of positive externalities in consumption means that market equilibrium without government intervention will result in the amount of services consumed being less than the optimal amount in terms of maximising public welfare. This occurs because individual economic agents, when deciding to purchase and consume an additional unit of a good, consider only the personal utility received, which is less than the utility for the whole society, leading to underconsumption. There are various ways in which the government can intervene to correct such "market failures", such as subsidies [63]. In practice, instead of subsidising each individual patient, the state subsidises medical organisations. Together with the presence of compulsory health insurance, this forms the basis of modern health-care systems in countries with models similar to the health-care system in the Russian Federation [64].

4.2. Consequences of State Intervention

In fact, through the actions of the state, health services begin to be characterised by the properties of public goods. This is due to characteristics like non-excludability and

non-competitiveness. [10]. The fulfilment of these properties can be interpreted in various ways. For instance, non-excludability suggests that it is impossible to offer a service to a single consumer without providing it to all others, and to a certain extent, universal access to healthcare implies this.

On the other hand, the non-competitiveness property is satisfied in a more truncated form, because when a doctor sees a patient, they cannot see a second patient at the same time. In this case, the second patient is still seen, but at a later time, which leads, in practice, to long queues at the doctor's office [65]. In such cases, the concept of quasi-public services is often used in the literature [25]. In fact, it would be more accurate to consider the system as a whole as a quasi-public good, rather than each individual service in the health care system. As its main characteristic its throughput capacity per unit of time can be considered. For example, if there are 20 doctors working in the system, they can serve a larger number of patients with less waiting time than if there are only 10 doctors working in the system, all other things being equal.

This is analogous to a public swimming pool with free access, but queues. In the case of health care, the size of the system, i.e., its capacity, is determined to a greater extent by the state. In fact, this involves an equilibrium in the volume of services provided. Although this is determined by the interaction of supply and demand, the peculiarities of the market, combined with the fact that there is a deficit of services on the market, which can be confirmed by the presence of queues, suggests that the state, by influencing the supply of services, such as by increasing the number of doctors, directly affects the equilibrium level of consumption. The state determines the interest rate that characterises the level of payments to the mandatory health-insurance funds and participates in the additional financing of the health care system [66]. The increasing role of added funding in the health-care system is partly due to the "stowaway" issue arising from unrestricted access to health-care services regardless of patient contributions.

4.3. Approach to Determining the Optimal Number of Doctors

In the literature, Samuelson's equation [10] is commonly used to determine the optimal quantity of public goods in the context of maximising public welfare. According to this equation, the volume of public goods is considered optimal if the total marginal utility of all consumers is equal to the marginal cost of its production. Conditions are assumed in which an increase in the volume of public goods always leads to an increase in the utility of their consumption, but each additional unit leads to an increasingly small increase. In this case, the costs increase at an accelerated rate as the volume of public goods produced increases.

Let the production of health care services be determined by the required number of specialist doctors. All other costs related to medical personnel, equipment, and other infrastructure are determined by the number of doctors. That is, from the point of view of society, we have a cost function of the form (1) and a utility function of the form (2). Next, the public welfare indicator can be expressed by Formula (3), and the condition for maximising the level of public welfare is given by Formula (4):

$$f_1 = c(y) \tag{1}$$

$$f_2 = v(y) \tag{2}$$

$$W(y) = v(y) - c(y) \tag{3}$$

$$v\prime(\overline{y}) = c\prime(\overline{y}) \tag{4}$$

where y is the number of physicians, through which the volume of services provided, and the scale or throughput of the health-care system is determined; $c(y)$ is the cost function, indicating the total cost of providing the work of doctors in a particular region; $v(y)$ is the utility function, measuring the total benefits received by society due to the work of the corresponding number of doctors in a particular territory; $W(y)$ represents the public

welfare indicator, which characterises the difference between the costs associated with supporting the work of doctors and society's benefits from their work in a particular territory; $v'(\overline{y})$ is the derivative of the function $v(y)$ at a specific value of $y = \overline{y}$, showing the amount of additional benefits received by society from the work of the respective doctor; $c'(y)$ is the derivative of the function $c(y)$ at a specific value of $y = \overline{y}$, showing the amount of additional costs incurred by society in supporting the work of the respective doctors.

Formula (4) is a necessary and sufficient condition for maximisation, in view of the corresponding properties of the cost and utility functions, namely $v'(y) > 0$, $v''(y) < 0$ and $c'(y) > 0$, $c'^{(y)} \geq 0$ for any $y > 0$, $c(0) = 0$. The economic interpretation of the introduced properties of the considered functions is as follows. Each additional doctor will bring additional benefits, but the magnitude of these benefits will decrease. In terms of costs, hiring an additional physician and providing him or her with a work environment will always incur additional costs, as more resources will be expended to find new qualified personnel. This may be due, for example, to the limited number of personnel in the area, which will require more effort and resources to attract new personnel, particularly to cover transportation and other transaction costs.

For simplicity, the utility function is given for society as a whole, without distinguishing between the utilities of individual patients and externalities. This is due to the fact that in practice, it is rather labor-intensive to derive the utility functions of individual patients or the influence of external effects. Therefore, this paper proposes an alternative way of estimating utility.

Let us give an economic interpretation of Formula (4). If $v'(\overline{y}) > c'(\overline{y})$ is fulfilled, the last hired doctor still brings more benefits to society than costs, and therefore, taking into account the considered properties, it is necessary to hire one more doctor, i.e., there is an underproduction of services in health care. That is, the indicator of public welfare can be increased by increasing the number of doctors. If $v'(\overline{y}) < c'(\overline{y})$ is fulfilled, hiring the last doctor brings more costs to society than benefits and, therefore, there is an overproduction of services. Furthermore, the maximisation of the indicator of public welfare can only be achieved with a specific number of doctors, when the equality of marginal utility and marginal cost functions is ensured.

In order to use Formula (4), it is necessary to calculate the value of the marginal cost, which is beyond the scope of this study, but does not seem difficult in any case, given the available information on current and potential costs. It is also necessary to obtain the function of marginal social utility, and here, we propose to express it in the form of the product of the index characterising the increase in the number of lives saved when hiring an additional doctor by the cost of one life saved: (p^{life}) (5). Consequently, Equation (4) takes on the form of (6). The question of estimating the cost of a life saved is also beyond the scope of this paper and can be considered both in a simple form, other factors being equal, and taking into account its expected duration and qualitative characteristics, which are relevant, for example, when choosing between doctors with different profiles, medical procedures, and other alternatives.

$$v'(y) = death_heart'_y \times p^{life} \tag{5}$$

$$death_heart'_y(\overline{y}) \times p^{life} = c'(\overline{y}) \tag{6}$$

where *death_heart* is the function demonstrating the correlation between the indicator that characterises cardiovascular disease mortality rates and the level of cardiologist availability in a given region (availability level). The value $death_heart'_y$ is the derivative of the "*death_heart*" function and illustrates the impact of a one-unit increase in the indicator measuring the availability of cardiologists on mortality rates from cardiovascular diseases. Specifically, the derivative shows how many more lives can be saved by hiring an additional cardiologist. The value p^{life} is the economic valuation of the cost of a human life. The value $death_heart'_y(\overline{y})$ characterisies the increase in the number of lives saved due to the work of the doctor concerned.

The main empirical aim of this paper is to derive the $death_heart'_y$ function. In the following, different model specifications are proposed that allow this. It is important to note that this function can be evaluated as a constant or as a function directly dependent on the number of physicians, e.g., allowing for the diminishing contribution of each additional physician. The most promising approaches include variants that allow the contribution of an additional physician to be estimated while taking into account other indicators of the area, including socioeconomic and demographic characteristics.

5. Methods and Data

5.1. Data

This paper uses annual data from 83 regions in the Russian Federation, for which information was available for the period from 2012 to 2019 and for which the relevant statistical observations for the period under consideration were available, provided by the Federal State Statistics Service of Russia [6]. The description of all variables and the approach to their calculation is given in Table 1. The data can be found in Supplementary Materials.

Table 1. Description of variables.

No.	Designation	Factor	Method of Calculation and Measurement
1	death_heart	Mortality from CVD	Mortality from diseases of the circulatory system (number of deaths per 100,000 members of the population population)
2	doctors_heart	Number of cardiologists (cardiologists' availability)	Number of cardiologists per 100,000 members of the population
3	vodkat	Alcohol consumption	Consumption of vodka products (vodka), decalitres per person over working age
4	tabakt	Tobacco consumption	Consumption of tobacco products (sales), RUB per person over working age
5	unempl	Unemployment	Unemployment rate (according to sample labor-force surveys; in percentage form)
6	educ_high	Higher education	Estimation of the share of the population with higher education in the region (number of students enrolled in bachelor's, specialist, and masters programmes per 10,000 population)
7	poor	Poverty rate	Proportion of poor (income below the subsistence minimum; in percentage form)
8	old	Proportion of the elderly	Share of people older than working age (in percentage form)
9	city	Percentage of urban population	Share of the urban population in the total population, in percentage form
10	sex_	Male-to-female ratio	Women per 1000 men
11	marriage	Marriage	Total marriage rates per 1000 members of the population (ratio of marriages formalised during a calendar year to the average annual population)
12	divorce	Divorceability	Total divorce rates per 1000 members of the population (ratio of marriages dissolved during a calendar year to the average annual population)
13	inc_real	Real per capita income	Nominal income divided by the cost of a fixed set of consumer goods and services
14	pollut_air_p	Air pollution	Pollutant emissions, thousand tons per person
15	pollut_water_ter_p	Water pollution	Emissions of pollutants, thousand cubic metres per sq.m. per person)

Table 1. *Cont.*

No.	Designation	Factor	Method of Calculation and Measurement
16	ill_heart	CVD incidence rate	Diseases of the circulatory system, number, registered diseases per 1000 members of the population
17	doctors_neoplasms_sosed	The average level of provision of oncologists in neighbouring regions (neighbours—all other regions of the Russian Federation)	Average weighted level of provision of oncologists in neighbouring regions based on the matrix of squared inverse distances (number of doctors per 100,000 members of the population)
18	doctors_neoplasms_sosed_1	Average level of provision of oncologists in neighbouring regions (nearest neighbours)	The average level of provision of oncologists in neighbouring regions that have a common border with the region under consideration (number of doctors per 100,000 people of the population)
19	doctors_neoplasms_sosed_2	Average level of provision of oncologists in neighbouring regions (nearest neighbours and their neighbours)	The average level of provision of oncologists in neighbouring regions that have a common border with the region under consideration or a common border with a region that has a common border with the region under consideration (number of doctors per 100,000 people of the population)
20	stud_medvuz_pop_sosed	The average level of provision of medical students in neighbouring regions (neighbours—all other regions of the Russian Federation)	The average level of provision of medical students (the number of students studying in medical specialties per 1000 population) in neighbouring regions based on the matrix of squared inverse distances
21	ussrmedvuz_sosed	The average level of provision of medical institutions in neighbouring regions in 1991 (neighbours—all other regions of the Russian Federation)	The average level of provision of medical institutions (presence or absence of a medical school) in neighbouring regions in 1991 based on the matrix of squared inverse distances (number of medical institutions)

To answer the formulated research question, it is necessary to consider as a dependent variable the mortality rate from cardiovascular diseases in the regions in the Russian Federation. In addition to assessing the direct impact of the variable characterising the availability of qualified medical personnel, control variables are considered in the modelling. The variables characterising the level of alcohol and tobacco consumption, unemployment, education, poverty, the proportion of the elderly, the proportion of the urban population, the ratio of men to women, marriage and divorce rates, real income, air and water pollution, and the incidence of cardiovascular diseases are considered as control variables in the basic version of the model.

To calculate the variables characterising the average level of the corresponding indicators in neighbouring regions, including doctors_neoplasms_sosed, doctors_neoplasms_sosed_1, doctors_neoplasms_sosed_1, doctors_neoplasms_sosed_2, stud_medvuz_pop_sosed, ussrmedvuz_sosed, different approaches to the definition of neighbours were used.

Next, the algorithm of instrumental-variable formation based on different types of spatial matrix was considered, using the example of an indicator characterising the average level of availability of oncologists in neighbouring regions. Spatial matrices characterised the weights used to calculate the average values of indicators in neighbouring regions for a given region. This study considers three types of spatial matrix.

The first type was the spatial matrix of the regions in the Russian Federation, which provides information about neighbouring regions that directly share a common border. That is, for each region, all other neighbouring regions were selected with equal weight. For example, if a region had only two neighbours, then when calculating the average level of a parameter in its neighbours, their arithmetic mean was taken.

The second type of spatial matrix was considered in a similar way, but the neighbours were both the nearest neighbours, with a direct common border, and regions that share a common border with the nearest neighbours, i.e., regions that share a common border with the region under consideration.

The third type of spatial matrix considered all the other regions in the Russian Federation as neighbouring regions. However, the squares of the inverse distances between the considered region and all the other regions were considered as weights. Economic distances were considered as distances taking into account the presence of transport.

Accordingly, the first, second, and third types of spatial matrix allow us to obtain weights for the calculation of the variables doctors_neoplasms_sosed_1, doctors_neoplasms_sosed_2, doctors_neoplasms_sosed, respectively.

5.2. Application of the Instrumental-Variables Method

The instrumental-variables approach is essential in advanced econometric modelling as it enables the resolution of various issues, such as reverse causality, omitted variables, and specific data characteristics that arise during the modelling process [62]. This, in turn, allowsthe identification of the potential underestimation of the indicator's impact on mortality rates from cardiovascular diseases, which characterises the level of availability of cardiologists. Comparing the results obtained through regressions with instrumental-variables methods and without them (testing Hypothesis 1) would allow the achievement of this objective. Additionally, a more precise assessment of the causal impact would provide reliable outcomes for testing the second hypothesis.

In practice, instrumental variables usually have two main requirements. They must satisfy the properties of relevance and exogeneity. The relevance property implies that the instrumental variable must have an effect on the variable whose effect on the dependent variable is to be estimated. In addition to its theoretical justification, this property can be tested using various tests. In practice, the most commonly used test is the Cragg–Donald Wald F-statistic (or F-statistic in first-stage regression). The exogeneity property implies that the instrumental variable is not related to the dependent variable in any way, except through the variable whose influence is estimated in the paper. This property is usually justified by economic intuition and is not directly tested. However, if there is at least one instrument whose exogeneity is not in doubt, other instruments can be tested for exogeneity using the Sargan test [67].

This study evaluates the impact of the indicator of the availability of specialist medical personnel—cardiologists—on the mortality rate from cardiovascular diseases. In fact, it is necessary to find instrumental variables that would have an impact on the indicator of the availability of cardiologists, but that would not be associated with the mortality rate from cardiovascular diseases. The instrumental variables considered in this paper are: three different versions of the indicator characterising the average level of availability of oncologists in neighbouring regions, calculated on the basis of different spatial matrices (doctors_neoplasms_sosed, doctors_neoplasms_sosed_1, doctors_neoplasms_sosed_2), the average level of provision of medical students in neighbouring regions (neighbours—all other regions of the Russian Federation) (stud_medvuz_pop_sosed), and the average level of provision of medical institutions in neighbouring regions in 1991 (neighbours—all other regions of the Russian Federation) (ussrmedvuz_sosed).

Next, the fulfilment of the relevance properties for the instrumental variables under consideration is considered. Will the relevance requirement be met? If there is a high availability of doctors, especially oncologists, around a region, it is more likely that this region will also have a relatively high availability of medical personnel. There may be a direct link. For example, it may be possible to attract personnel from neighbouring regions.However, there may also be unobserved factors that contribute to more favorable conditions for attracting physicians. For example, if the neighbouring regions have a high number of cardiologists, then perhaps there are specialist educational institutions nearby,

or, in general, this cluster of regions may have favorable conditions for attracting doctors, which could be due to geographical or even historical reasons.

Similar reasoning can be applied to the variables characterising the average level of medical students in neighbouring regions and the average level of medical institutions neighbouring regions in 1991. Are the exogeneity requirements satisfied? The main problem in this case is that there may be unobserved characteristics that characterise clusters of areas. For example, a high level of availability of oncologists in neighbouring regions may mean that this cluster of regions has a generally high level of development and, thus, the same level of development determines both a high level of availability of oncologists in neighbouring regions and, for example, a relatively low level of mortality from CVDs in the region under consideration. This is an example of one of the channels showing that the instrument can be related to the dependent variable in a different way, which means that the exogeneity property is violated. The way in which the average level is calculated is also important. For example, if only a close circle of neighbours is considered, it is more likely that exogeneity is violated, because closer areas are more likely to have the same characteristics.

The variable stud_medvuz_pop_sosed_, for example, has a similar problem because the level of endowment in neighbouring regions may also affect both the number of medical students per capita and the level of endowment in the region under consideration, leading to a violation of the exogeneity property. In this regard, the instrumental variable ussrmedvuz_sosed_, which describes the average level of medical facilities in neighbouring regions in 1991, seems to be the most promising.

The fact that the data describe the values of the corresponding characteristics of the territories 20 years ago, after which significant changes occurred both in the health sector and in other areas of the state structure, makes it more certain that this variable fulfils the exogeneity property.

5.3. Models Considered

To evaluate the impact of cardiologists' availability (the number of cardiologists per 100,000 members of the population) on cardiovascular mortality, several models will be estimated. These models (m1, m2, and m3) and their variants differ based on the set of instrumental variables used.

Nonlinear models will be utilised to examine whether the contribution of each additional physician to the total lives saved varies with the number of physicians.

- A regression model (7) based on spatial sampling (m1). Versions without the instrumental-variables method (m1.1), and with the instrumental-variables method, considering doctors_neoplasms_sosed and ussrmedvuz_sosed_ (m1.2), doctors_neoplasms_sosed, ussrmedvuz_sosed and the squares of these variables (m1.3),), doctors_neoplasms_sosed, stud_medvuz_pop_sosed, ussrmedvuz_sosed (m1.4), and, simultaneously, doctors_neoplasms_sosed, stud_medvuz_pop_sosed, ussrmedvuz_sosed and the squares of these variables (m1.5) as instrumental variables.
- Regression model (8) based on panel data (m2). Versions without instrumental-variables method (m2.1), and with instrumental-variables method, considering doctors_neoplasms_sosed, doctors_neoplasms_sosed_1, and doctors_neoplasms_sosed_2 as instrumental variables (m2.2)
- This study employs a regression model (9) based on panel data (m3), utilising spatial econometrics via the spatial Durbin approach (SDM). This approach considers spatial autocorrelation for both the dependent variable and other variables [68,69]. The model supposes that the mortality rate in a specific locality is affected not just by the features that are distinctive to that locality, but also by the mortality rate of neighbouring areas and the average level of all the other characteristics of these neighbouring areas.

$$\begin{aligned}\text{death_heart}_i = {} & \beta_0 + \beta_1 \times \text{doctors_heart}_i + \beta_{1_2} \times \text{doctors_heart}_i{}^2 + \beta_2 \times \text{vodkat}_i \\ & + \beta_3 \times \text{tabakt}_i + \beta_4 \times \text{unempl}_i + \beta_5 \times \text{educ_high}_i + \beta_6 \times \text{poor}_i \\ & + \beta_7 \times \text{old}_i + \beta_8 \times \text{city}_i + \beta_9 \times \text{sex}_i + \beta_{10} \times \text{marriage}_i \\ & + \beta_{11} \times \text{divorce}_i + \beta_{12} \times \text{inc_real}_i + \beta_{13} \times \text{pollut_air_p}_i \\ & + \beta_{14} \times \text{pollut_water_ter_p}_i + \beta_{15} \times \text{ill_heart}_i + \varepsilon_i \end{aligned} \quad (7)$$

$$\begin{aligned}\text{death_heart}_{it} = {} & \alpha_i + \beta_1 \times \text{doctors_heart}_{it} + \beta_{1_2} \times \text{doctors_heart}_{it}{}^2 + \beta_2 \times \text{vodkat}_{it} \\ & + \beta_3 \times \text{tabakt}_{it} + \beta_4 \times \text{unempl}_{it} + \beta_5 \times \text{educ_high}_{it} + \beta_6 \times \text{poor}_{it} \\ & + \beta_7 \times \text{old}_{it} + \beta_8 \times \text{city}_{it} + \beta_9 \times \text{sex}_{it} + \beta_{10} \times \text{marriage}_{it} \\ & + \beta_{11} \times \text{divorce}_{it} + \beta_{12} \times \text{inc_real}_{it} + \beta_{13} \times \text{pollut_air_p}_{it} \\ & + \beta_{14} \times \text{pollut_water_ter_p}_{it} + \beta_{15} \times \text{ill_heart}_{it} + \varepsilon_{it} \end{aligned} \quad (8)$$

$$\begin{aligned}\text{death_heart}_{it} = {} & \alpha_i + \rho \times W \times \text{death_heart}_{it} + \beta_1 \times \text{doctors_heart}_{it} + \beta_2 \times \text{vodkat}_{it} \\ & + \beta_3 \times \text{tabakt}_{it} + \beta_4 \times \text{unempl}_{it} + \beta_5 \times \text{educ_high}_{it} + \beta_6 \times \text{poor}_{it} \\ & + \beta_7 \times \text{old}_{it} + \beta_8 \times \text{city}_{it} + \beta_9 \times \text{sex}_{it} + \beta_{10} \times \text{marriage}_{it} \\ & + \beta_{11} \times \text{divorce}_{it} + \beta_{12} \times \text{inc_real}_{it} + \beta_{13} \times \text{pollut_air_p}_{it} \\ & + \beta_{14} \times \text{pollut_water_ter_p}_{it} + \beta_{15} \times \text{ill_heart}_{it} \\ & + \gamma_1 \times W \times \text{doctors_heart}_{it} + \gamma_2 \times W \times \text{vodkat}_{it} + \gamma_3 \times W \times \text{tabakt}_{it} \\ & + \gamma_4 \times W \times \text{unempl}_{it} + \gamma_5 \times W \times \text{educ_high}_{it} + \gamma_6 \times W \times \text{poor}_{it} \\ & + \gamma_7 \times W \times \text{old}_{it} + \gamma_8 \times W \times \text{city}_{it} + \gamma_9 \times W \times \text{sex}_{it} \\ & + \gamma_{10} \times W \times \text{marriage}_{it} + \gamma_{11} \times W \times \text{divorce}_{it} + \gamma_{12} \times W \times \text{inc_real}_{it} \\ & + \gamma_{13} \times W \times \text{pollut_air_p}_{it} + \gamma_{14} \times W \times \text{pollut_water_ter_p}_{it} \\ & + \gamma_{15} \times W \times \text{ill_heart}_{it}\text{a} + \varepsilon_{it} \end{aligned} \quad (9)$$

where β_i is the regression coefficients, ε_i is the random error, t is the year; α_i characterises the fixed effect of region i independent of year t, W is a matrix characterising the spatial component in the model, and ρ—is a coefficient reflecting the presence of spatial effects.

All the models are non-linear, considering both the variable doctors_heart and its square. This approach is necessary to identify the decline in additional doctors' contributions to the total number of lives saved (test of Hypothesis 2). To test Hypothesis 1, it would suffice to compare coefficients of the doctors_heart variable between models using and not using the instrumental-variables method. The m3 model is necessary to examine the exogeneity property of the instrumental variables under consideration. This is undertaken by illustrating that there is no correlation between the mortality rates from cardiovascular disease in neighbouring regions.

6. Results

The initial data analysis, including pairwise correlation coefficients, did not identify any potential hindrances to estimating the aforementioned models. The details of the data's statistical properties are outlined in Table 2.

Further details on the statistical properties of the variables under analysis, including their distribution and associated correlation matrix, can be found in Appendix A (Figure A1). A strong correlation was found between the variables that measured marriage and divorce rates and those that detailed the ratio of males to females, as well as the number of people above working age, with correlation coefficients of 0.68 and 0.74, respectively. These findings were anticipated in light of the socio-economic and demographic traits of the Russian regions, particularly the population pyramid. Although the indicators themselves were not significantly elevated, the instrumental-variables method mitigated any potential issues.

Table 2. Statistical properties of considered data.

Variable	Mean	Std. Dev.	Min	Max
death_heart_	629.73	184.91	131.20	1204.70
doctors_heart_	8.87	2.73	0.59	19.72
vodkat_	0.79	0.45	0	3.44
tabakt_	2401.93	2249.27	40.09	19119.94
unempl_	6.49	4.22	0.80	47.70
educ_high_	284.80	117.96	0	786.00
poor_	14.25	5.01	5.60	37.80
old_	23.60	4.81	8.30	31.30
city_	70.16	13.01	28.90	100.00
sex_	1144.93	53.43	961.00	1236.00
marriage_	7.28	1.34	3.80	11.10
divorce_	4.39	1.03	0.50	7.00
inc_real_	7.29	1.89	3.87	16.41
pollut_air_p_	0.17	0.29	0.0005	2.34
pollut_water_ter_p_	0.00	0.02	0	0.17
ill_heart_	31.27	10.58	11.90	98.40
doctors_neoplasms_sosed_	5.0729	0.63	3.71	7.65
doctors_neoplasms_sosed_1_	5.0734	1.07	2.28	8.83
doctors_neoplasms_sosed_2_	5.03	0.82	2.28	8.17
stud_medvuz_pop_sosed_	4.08	1.75	1.23	10.71
ussrmedvuz_sosed_	0.57	0.20	0.24	2.23

Table 3 presents the findings from the non-linear-model estimations, which assume that the value of each additional physician in saving lives can vary as the number of physicians increases.

Thus, according to the results obtained in m1.5, at the level of cardiologist availability of one doctor per 100,000 members of the population, the marginal impact on the number of lives saved in relation to cardiovascular diseases is 124 people per 100,000. However, further growth in the level of provision of one doctor per 100,000 population leads to an increasingly low level of mortality reduction, decreasing by 10 people per 100,000. All the versions of models m1 and m2 that utilised the instrumental-variables method in their estimations yielded comparable outcomes. Conversely, in the m1 and m2 models that did not employ the instrumental-variables method, the contribution of cardiologists was significantly underestimated or even counterintuitive.

When examining the estimation outcomes of the m3 model, the spatial rho coefficient is important. It was statistically insignificant, thereby allowing us to deduce that the mortality rate attributed to cardiovascular diseases in certain regions lacked a correlation with corresponding indicators observed in adjacent regions.

The precision of the estimates of the impact of the remaining variables is beyond the scope of this study, since they were treated only as control variables. Quasi-experimental methods were not used in their estimation, so the results may be both under- and overestimates due to various econometric problems. Robust estimators were used to estimate the regression models, which addressed potential problems of heteroscedasticity and autocorrelation in the data.

Table 3. Results of the evaluation of the considered nonlinear models using the square of the variable characterising the level of staffing.

			m1			m2		m3
Variables	**m1.1**	**m1.2**	**m1.3**	**m1.4**	**m1.5**	**m2.1**	**m2.2**	
Number of cardiologists	−43.948 ***	−138.349 *	−165.707 ***	−118.737 *	−134.193 ***	7.237	−101.272	−4.262
	(6.054)	(76.627)	(39.067)	(65.140)	(38.319)	(8.651)	(61.590)	(2.713)
Number of cardiologists squared	1.720 ***	5.386	6.907 ***	4.199	5.134 ***	−0.712 *	3.177	
	(0.297)	(4.494)	(1.952)	(3.775)	(1.925)	(0.390)	(3.382)	

Table 3. *Cont.*

			m1			m2		m3
Variables	**m1.1**	**m1.2**	**m1.3**	**m1.4**	**m1.5**	**m2.1**	**m2.2**	
Alcohol consumption	37.038 ***	6.890	2.107	9.499	7.441	10.792	6.134	−30.974 *
	(11.201)	(17.904)	(15.761)	(17.730)	(15.942)	(11.916)	(24.615)	(16.767)
Tobacco consumption	−0.000	0.002	0.002	0.001	0.002	0.002	−0.000	0.001
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)	(0.002)	(0.002)
Unemployment	1.345	−0.466	−1.223	0.124	−0.341	−1.841	−5.895 **	−3.924 ***
	(1.747)	(3.197)	(2.421)	(2.917)	(2.344)	(1.562)	(2.778)	(1.257)
Higher education	−0.020	0.113	0.076	0.156	0.122 *	0.264 **	0.267 **	−0.073
	(0.045)	(0.171)	(0.075)	(0.141)	(0.068)	(0.102)	(0.116)	(0.067)
Poverty rate	−6.040 ***	−9.975 ***	−10.718 ***	−9.524 ***	−9.879 ***	0.003	−0.200	−0.507
	(1.276)	(2.606)	(2.196)	(2.433)	(2.056)	(1.972)	(2.746)	(1.513)
Proportion of the elderly	25.756 ***	20.865 ***	20.422 ***	20.980 ***	20.889 ***	−24.394 ***	−6.315	25.843 ***
	(2.489)	(3.044)	(3.101)	(3.012)	(2.965)	(6.646)	(7.952)	(8.979)
Percentage of urban population	−0.007	1.270 *	1.388 **	1.236 *	1.263 **	3.431	5.801 *	0.656
	(0.463)	(0.659)	(0.672)	(0.646)	(0.635)	(3.580)	(3.460)	(2.800)
Male-to-female ratio	0.672 ***	1.064 ***	1.143 ***	1.014 ***	1.053 ***	3.308 ***	3.853 ***	1.651 **
	(0.165)	(0.277)	(0.224)	(0.253)	(0.210)	(0.869)	(0.968)	(0.785)
Marriage	50.351 ***	29.183 *	32.161 ***	25.159 *	28.326 ***	4.525	−4.726	10.669
	(5.886)	(17.521)	(9.077)	(14.716)	(8.367)	(4.553)	(9.563)	(6.554)
Divorceability	−15.529 *	−12.824	−15.881	−9.837	−12.189	−5.883	−4.806	−0.657
	(8.564)	(15.391)	(11.411)	(13.303)	(10.527)	(8.321)	(14.503)	(9.265)
Real per capita income	−23.553 ***	−27.231 ***	−29.471 ***	−25.382 ***	−26.839 ***	0.367	9.170	−8.792
	(3.541)	(8.316)	(4.992)	(7.250)	(4.718)	(10.421)	(13.510)	(7.992)
Air pollution	1.567	−31.135	−32.060	−32.246 *	−31.374 *	−44.614	−30.418	−39.453
	(16.393)	(20.010)	(20.659)	(19.092)	(18.853)	(41.202)	(37.749)	(27.904)
Water pollution	−1289.754 ***	−1870.618	−2740.490 **	−1101.606	−1707.327 *	234.476	1535.75	−1574.936 ***
	(222.212)	(2874.492)	(1069.974)	(2389.143)	(995.426)	(631.838)	(1087.8)	(556.820)
CVD incidence rate	−0.922 **	−0.407	−0.201	−0.565	−0.440	−1.158 *	−0.650	−0.075
	(0.407)	(0.773)	(0.558)	(0.684)	(0.536)	(0.587)	(0.603)	(0.452)
Constant	−544.969 ***	−235.739	−179.485	−269.151	−242.805	−2869.12 **		
	(146.947)	(213.257)	(187.345)	(207.218)	(188.606)	(1164.101)		
Spatial rho								−0.146
								(0.114)
Spatial X								+
Observations	664	664	664	664	664	664	664	664
R-squared	0.723	0.598	0.561	0.603	0.600	0.578	0.368	0.466
AIC	7998	8244	8302	8236	8241	6994	7262	6756
BIC	8074	8321	8379	8312	8317	7066	7334	6900
Number of regions						83	83	83

Source: compiled by the authors; robust standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

7. Discussion

In most of the instances in which the instrumental-variables method was employed, whether using models based on spatial sampling or those based on panel data, identical results were achieved. This indicates a considerable level of stability in the outcomes attained, enabling us to formulate an answer to the research question at hand. Specifically, an augmentation in the metric representing the extent of the supply of cardiologists resulted in a reduction in the rate of fatalities caused by heart-related conditions. The first hypothesis was verified. In models m1.1 and m2.1, the coefficient for the variable indicating the level of availability of cardiologists was significantly smaller than in models m1.2, m1.3, m1.4, m1.5, and m2.2. This suggests that the presence of false-positive relationships, as previously described, leads to a significant underestimation of the required relationship in cases of econometric modelling that do not use instrumental variables. Hypothesis 2 also received confirmation. Thus, in all the varieties of m1 and m2, in which the method of instrumental variables was applied, there was a conclusion about the decrease in the value of additional reductions in mortality from cardiovascular diseases due to the hiring of additional cardiologists if the indicator characterising the level of cardiologists' provision grew.

It is important to carefully consider version m1.5 of the m1 model, which utilised the variables doctors_neoplasms_sosed, stud_medvuz_pop_sosed, and ussrmedvuz_sosed as instruments. Of all the instrumental variables under consideration, the ussrmedvuz_sosed variable is the most exogenous. This is because it is challenging to identify convincing arguments to suggest that the presence of medical schools in adjacent regions in 1991 had a direct impact on cardiovascular disease mortality in 2012 or 2019 other than through the level of staffing. Although direct testing of the exogeneity property is not feasible, the Sargan test can be employed to enhance confidence in the exogeneity of the other instruments. This test makes it possible to evaluate the exogeneity of the variables in use,

with the stipulation that one of the variables is exogenous. When assessing m1.5, the null hypothesis is that the instruments are valid instruments, i.e., they are uncorrelated with the error term and cannot be rejected at a satisfactory level of significance. Focusing on the m1.5 variation of the m1 model, it is possible to express the relationship between the mortality rate caused by cardiovascular diseases (death_heart) and other factors, such as the level of provision of cardiologists (10). Consequently, the derivative concerning the doctors_heart variable can be expressed as (11).

$$\text{eath_heart} = -242.8 - 134.2\text{doctors_heart} + 5.13\text{doctors_heart}^2 + \ldots \quad (10)$$

$$\text{death_heart}'_{\text{doctors_heart}} = -134.2 + 10.26\text{doctors_heart} \quad (11)$$

Simultaneously, calculating the spatial rho coefficient in cubic metres instils confidence in the objective reflection of reality in the obtained results. It should be noted that when utilising parameter values in adjacent regions, such as doctors_neoplasms_sosed, stud_medvuz_pop_sosed, and ussrmedvuz_sosed as instrumental variables, there is a potential hazard, in that these variables may have an indirect influence on the modelled indicator via a subsequent chain. For instance, the availability of oncologists in adjacent regions may be correlated with the availability of cardiologists in those regions. Additionally, the presence of cardiologists in those areas may be linked to mortality rates caused by cardiovascular diseases. Furthermore, the mortality rate in those adjacent regions may also influence the mortality rate in the region analysed. If this is the case, it transpires that the instrumental variable used, such as the provision of oncologists in nearby regions, remains connected to the modelled variable, namely the mortality rate from cardiovascular diseases in the region under investigation, thus violating the exogeneity property. However, the insignificant statistical significance of the spatial rho coefficient suggests that the mortality rate from cardiovascular diseases in a specific region is not directly associated with the mortality rate in neighbouring regions. This leads us to believe that the instrumental variables employed are exogenous.

These findings are not incompatible with previous research. For instance, in one study [56], the use of quasi-experimental approaches to econometric modelling was neglected, resulting in an underestimation of the contribution that cardiologists make to the reduction in mortality from cardiovascular diseases due to reverse causality. Most research has established that the level of medical-personnel availability negatively affects the mortality rate across a range of diseases, including cardiovascular disease. This has also been documented in other studies [56–59]. At the same time, this study showcases an important finding regarding the diminishing returns achieved by recruiting additional physicians in the effort to decrease mortality rates related to cardiovascular diseases via the application of nonlinear models. This enables us to take a noteworthy stride towards establishing the ideal number of healthcare staff within the parameters of the proposed theoretical paradigm, through the assessment of the marginal utility and marginal expenses associated with employing supplementary medical personnel.

8. Conclusions

This study proposes a theoretical model for determining the equilibrium volume of services in the health-care sector using the example of the supply of cardiologists. This study differs from previous publications by comparing the utility and costs of hiring additional doctors, making it possible to ensure the maximisation of the public welfare indicator. It is demonstrated that, taking into account all the introduced economic parameters, the maximisation of the public welfare indicator can be achieved if such a number of doctors is hired that the marginal contribution to the growth of the public utility function from the last hired doctor is equal to the marginal cost of hiring them, taking into account the cost of providing conditions for their work. It was proposed to calculate the marginal public utility function as a product of the indicator characterising the increase in the number of

saved lives in the case of increasing the indicator of cardiologist provision by one unit by the cost of one saved life.

In the context of delineation, the primary empirical finding is the estimation of the indicator that characterises the rise in the number of lives saved in the event of a one-unit increase in the indicator of cardiologists' availability. An econometric model was developed and evaluated, using an instrumental-variables methodology with the author's own tools. This was used to identify the underestimation of relevant effects when using econometric modelling without quasi-experimental methods, as well as the diminishing returns from hiring more doctors to reduce mortality from cardiovascular diseases. To apply the instrumental-variables method, a distinct approach to instrumental-variable design was developed that diverges from existing methods by using different modifications of spatial matrices. Separate strategies for establishing the exogeneity of the instrumental variables used were also explored, including spatial-econometrics methods. According to the results obtained, at the level of cardiologist availability of one doctor per 100,000 members of the population, the doctors' marginal contribution to the number of lives saved from cardiovascular diseases is 124 people per 100,000. However, further growth in the level of provision of one doctor per 100,000 population leads to an increasingly low level of mortality reduction, decreasing by 10 people per 100,000 (11). This is more than three times higher than the estimates in the baseline models, in which the instrumental-variables method was not applied.

Regarding the implications of these findings, Formula (8), along with estimates of the cost of living and the cost function, enables the identification of the optimal number of cardiologists required within a territory. If a region is operating under financial constraints, evaluating the marginal contribution of doctors from other specialties and even other non-healthcare-funding sectors can aid in comparing their outcomes and in guiding management decisions in order to optimise public welfare. For instance, would employing a cardiologist or an oncologist result in saving more lives? Should funding be allocated towards hiring an additional doctor or constructing a pedestrian crossing near a school? The latter determines the practical relevance of the study in relation to developing novel approaches to management decision-making. This includes the potential to create evidence-based policy tools within the health care sector.

Important limitations of this study include the failure to consider that the impact of the indicator characterising the level of medical-personnel availability on mortality rates from relevant disease types may vary, depending on the characteristics of certain territories. The modelling conducted did not account for these differences. For instance, the influence of physicians could be greater in areas with a higher proportion of elderly people among the population or other specific parameters. However, the evaluation was conducted objectively, considering all the relevant factors. Future research must rigorously assess the marginal public utility function of recruiting further medical staff. Specifically, this can be achieved through the creation of models that account for the impact of doctors on reducing cardiovascular disease mortality rates in relation to the unique characteristics of the region. One possible approach could involve employing non-linear models with logarithmic transformations. It is necessary to assess the validity of the suggested formation algorithm and the justification for using instrumental variables within this study, considering various spatial neighbourhood matrices.

Supplementary Materials: The following supporting information can be downloaded at: https://figshare.com/projects/How_to_determine_the_optimal_number_of_cardiologists_in_the_region_/178302, Computer Code (NAR_for_article.do, STATA 14.2 version, Data, Figure A1).

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Data Availability Statement: The data presented in this study are openly available at the https://figshare.com/projects/How_to_determine_the_optimal_number_of_cardiologists_in_the_region_/178302, (accessed on 10 March 2023).

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

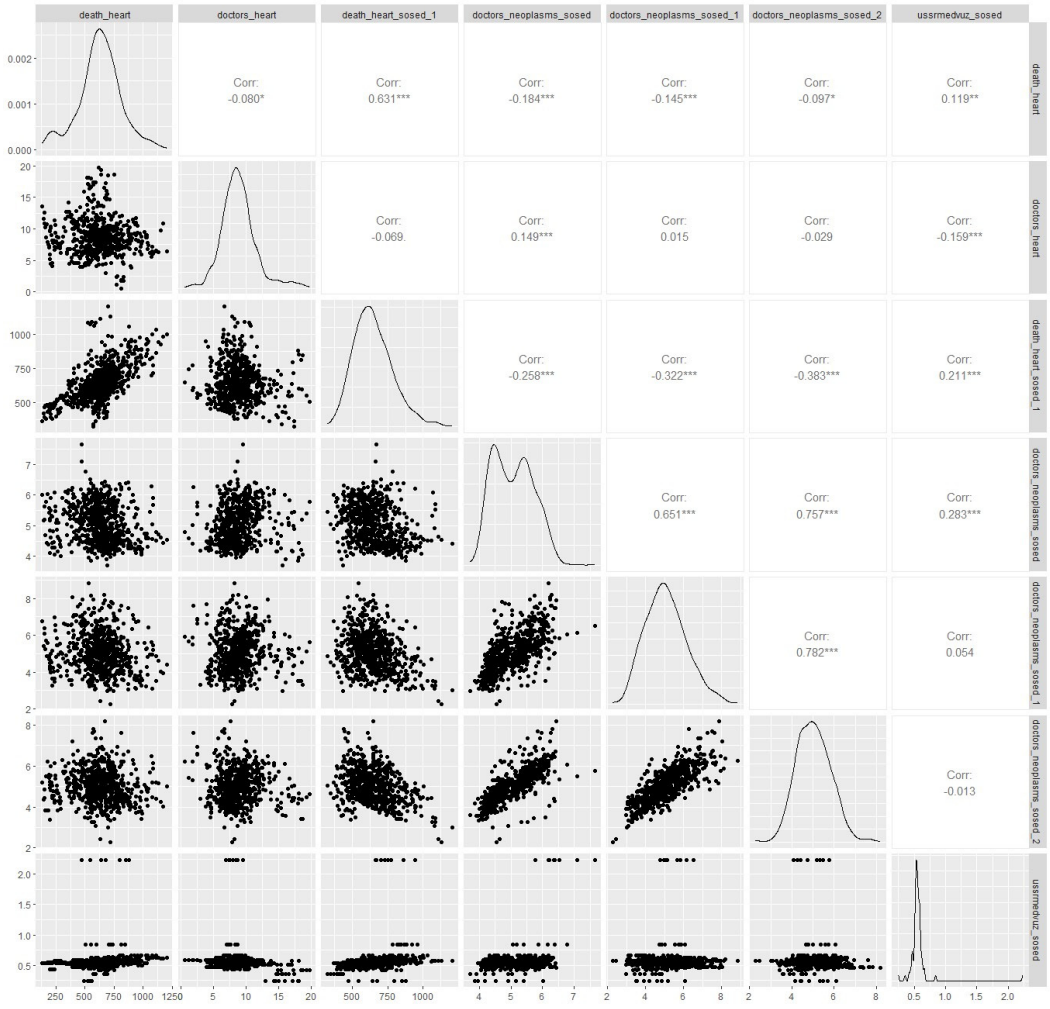


Figure A1. Correlation matrix and distribution of the dependent variable and the indicator of cardiologist availability, as well as the considered instrumental variables (source: compiled by the authors).

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