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Research article

Possibilities and limits of modelling of long-range economic consequences of air pollution – A case study

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ABSTRACT

Air pollution is the biggest environmental problem in modern societies, causing considerable health damage and requiring substantial financial resources for health care. The goal of the study is to demonstrate the adverse economic consequences of air pollution on example of a small, open Central European country, Hungary, and to provide quantified financial arguments for macroeconomic decision-making for the development of a long-term energy strategy. On the basis of the Cobb-Douglas production function and Solow-Swann model of dynamic economic systems a simple and robust model was constructed to estimate and predict economic losses, caused by the pollution. On base of results it is obvious, that on base of macroeconomic theory and combination of various, publicly available, quality-controlled statistical resources quantifiable models can be constructed to characterise the economic consequences of air pollution, but it should be taken into consideration, that the reliability of economic models considerably depends on their initial parameters and practical validity of assumptions, based on which the underlying economic theories were built. The most important economic burden of air pollution is caused by the loss of working–age population, resulting in a decrease of 4.1–9.4 % a year in Gross Domestic Product (GDP) in the next fifty years. The additional burden of health care costs amounts to 0.1 % of GDP. Reducing air pollution is not only a quality of life improvement but also an investment into the economic development. Notwithstanding of statistical biases it could be proven the importance of combination health economic and econometric methods in preparation of more efficient environmental-related socio-economic decisions.

1. Introduction

1.1. Air pollution, as a prominent environmental problem

It is well-known that the environmental pollution is a considerable factor in the decline in quality of life quality [1]) in general and in health status in particular [2], but there are few, methodically well-documented, rigorous analyses of the economic burden of

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environmental pollution [3–7]. The aim of the present article is to fill the gap between widely accepted but not proven assumptions about the adverse effects of environmental pollution and hard economic facts, based on carefully selected, internationally recognized databases and well-founded replicable research methods. The geographic scope of the study is Hungary, a small, open economy in Central Europe, but the article is written in such a detailed way that the results of the research can be checked and replicated in any other geographic area, and the authors hope to encourage researchers to undertake similar studies.

Air pollution is considered the greatest environmental risk facing the Earth [8]. The adverse health consequences of air pollution are well-addressed in the epidemiologic literature [9–14]. There is hard evidence of a positive correlation between air pollution and global warming [15] air pollution is therefore at the heart of policy-making [16,17].

It is well known that air pollution is one of the most important public health problems. It is a global challenge as a focus of research. Precisely defining the economic consequences of air pollution is a rather difficult due to the high variability of exposition and the relatively lesser-known relationships between air pollution and epidemiologic consequences [18].

The World Health Organisation (WHO) estimates that the annual number of deaths exceeds one million [19].

Air pollution has two main adverse consequences for human health. On the one hand, larger particles in polluted air have direct adverse histological and immunomodular effects, on the other hand, these particles are cariers of heavy metal and hydrocarbon molecules. Pollutants, e.g. ozone, carbon monoxide, sulphur dioxide, nitrogen dioxide and small-size motes could cause considerable problems in the lower respiratory tract [20].

The short-term consequences of air pollution are general discomfort, due to the irritation of the mucosa, followed by headaches, vertigo and eye or skin irritation. Long exposure to polluted air has wide-ranging, negative effects on human health. The primary targets of air pollution are the cardiovascular and respiratory systems, but a considerable number of mental problems can be a consequence of air pollution, too. Air pollution could lead to cancer or death [20].

The incidence of neoplasms shows a significant correlation with the incidence of air pollution in the medical history of patients with chronic lung diseases [21].

Exposure to polluted air results in adverse neuropsychiatric changes in children and adults. Air pollution is thought to play an important role in the development of neuro-degenerative diseases by causing oxidative stress, inflammation and mitochondrial damage in neurons, as well as in autism [22].

Short-time exposure to air pollutants can cause a number of health problems, e.g. cardiac failure and heart attack, and the short-time exposure can lead to coronary atherosclerosis and myocardial hypertrophy [23]. The association between the prevalence of acute cardiovascular diseases and air pollution is well documented [24], but the effects of air pollution on heart problems, which affects 23 million people globally are less well understood [25]. A meta-analysis by Shah et al. [26] found a significant association between air pollution, heart-related mortality and days in hospital. This fact highlights the importance of air pollution for health policy.

As a summary, it can be concluded that air pollution is an important public health problem, which the General Directorate of WHO refers to as a "silent public health emergency" and "the new tobacco".

The facts presented above highlight the wide range of causes of air pollution that affect the health of the population in different ways; therefore there is an urgent need for coordinated action, integrating the efforts of health care and economic professionals to expand our knowledge base, to develop practical decision-support studies and practical solutions.

1.2. Regulation of air pollution: results and challenges

Concerns about and legislative regulation of air pollution have a complex and contradictory history, since the complains about the polluted air in ancient Athens and Rome, through shock-like phenomenon in the mid-twentieth century, e.g. from the "great smog" in London to our days, in which a complex set of data collection and –management system helps to better understand the mutual connections between human activity and air quality [27].

From an economic policy perspective, it is an open question whether strict regulations in developed countries increase pollution in less developed parts of the world [28]. There is ample evidence [29–31]) that multinationals in the US and other developed countries are relocating their activities to countries with less stringent regulation. In opinion of Feng et al. (2020) the development in field of air pollution control in Europe and North America has achieved considerable results, especially in decreasing of pollution, but there remained problems, solution of which demand new approach [32]. Analysing the current problems of air pollution, the most important questions are as follows: long-lasting effects of former air pollution; high level of ammonia emission; air pollution problems in newly industrializing, fine particle emission; local emissions due to illegal activities; adverse effect of climate change, especially of heat waves just to name a few. In case of Hungary an especially important problem is the adverse environmental effects of the Russian-Ukrainian war, in the neighbourhood of the country.

Air pollution is of particular concern in countries with former centrally planned economies (as in the case of Hungary), due to low energy efficiency and a relatively weak legislative framework [33,34]. Hungary has seen a decline in air pollution in recent years [35], but this is due to the collapse of former industrial structure rather than to conscious policy measures [36–38].

1.3. Analysis of health-consequences of air pollution as an economic problem

1.3.1. Research on air-pollution-health –economic consequences nexus

Bibliometric analysis is a modern and efficient way to survey to landscape of the research, concerning the air-pollution – health-economy triangle. For this purpose, we have used the Web of Science database, which is widely acknowledged as a leading source of high-quality research publications [39]. We have applied the query:

TS=(((”air pollut*”) AND (“health*” OR “disease*”)) AND ((“Cost*”) OR (“econ*”)))

Altogether we have got 614 hits from this database. Obviously, the problematics of economic consequences of air pollution is gaining in importance in the academic literature (Fig. 1). A similar approach has been used by Xie and Zhu in 2022, but in our case we have focused just on problems of cost estimation aspects of this question [40].

The results were analysed based on triangulation method [41], trying to understand the problems from various points of view, lighting the air pollution-health- economy nexus from different angles.

In firs phase we have applied the Vosviewer software, developed to analyse the bibliometric data on base of network-analysis considerations [42]. We have applied this tool to determine the clusters of research topics, formatted on co-occurrence of words and expressions. Altogether 2751 connections could be identified. Out of these 231 keywords appeared more than five times. From these keywords we have removed such ones, which do not carry relevant information (e.g. if we search on air pollution effect on health, the most frequent word will be health). Synonyms and expressions, having the same meaning but written in various ways were merged. In this way 199 keywords remained. Our results are depicted in Fig. 2. Various keywords, classified into one cluster are depicted with the same colour. The relative position of the clusters are based on a two-dimensional projection. The frequency of various words is proportional with the size of circles, symbolising the words or phrases. Seven clusters could be separated. Obviously, there are considerable differences from point of view of members of components of various clusters and the diversity of them. A considerable number of words could be collected in Cluster A, this is a wide collection of research topics, focussing on adverse consequences of air pollution-mainly focussing on Chine. The Cluster B is a health policy related cluster, concentrating mainly, but not exclusively on infant health. The Cluster C is the research topics of analysis of the problem of air pollution form point of sociology and economic policy making. Cluster D is searching the mutual relations between the economic growth and air pollution. Cluster E is a rather technology oriented one, focussing on causes of air pollution, involving the problems of indoor pollution into the discussion. In this cluster India has a primarily role. Cluster F deals with problems of air pollution and emission, taking into consideration the consequences of global climate change. The Cluster G is a relatively compact cluster: here are the keywords and phrases, which are attaching to the application of estimation of monetary value of clean air by willingness to pay (contingent valuation) methods.

Analysing the set of data on epistemological basis by CitNetExplorere software of various publications, five clusters can be differentiated [43]. The largest cluster consists of a relatively large number of publications (323 papers, nearly of the total corpus). The focus of these publications is the influence of air pollution of health. The second largest cluster (180 papers) analysis the clear air as an economic public good. The third largest group of publications (95 papers) deals with the problems of regulation of air pollution. A relative small group of publications (46 papers) is devoted to the analysis of technological aspects of air pollution, involving some economic problems. The smallest cluster deals with long-range macroeconomic questions of the air pollution.

Cobo et al. (2011) developed a simple and transparent visualisation method for determination strategic importance of various research topics [44]. This approach is based on clustering of topics by the words and phrases, applied in title, keywords and abstract of publications, and the citation structure of the publications. The clusters are projected into a two-dimensional space. The horizontal axe shows the intensity of citation of the given topics by publications, categorised into another topics, the vertical axe shows the intensity of citation activity within the cluster of papers, categorised into the given topics. Topics with high intensity of citation are in upper right quadrat, these are the so-called motor themes. The developed, but isolated topics, specialists of which are discussing intensively between each other, are positioned into the upper right quadrat. The emerging or declining topics are in lower left quadrat, and the basic themes are in lower right quadrat. In case of the economic problems of air pollution we see a rather intuitive picture (Fig. 3). It is obvious, that the application of value of years and the contingent valuation methods became the basic part of the research. The

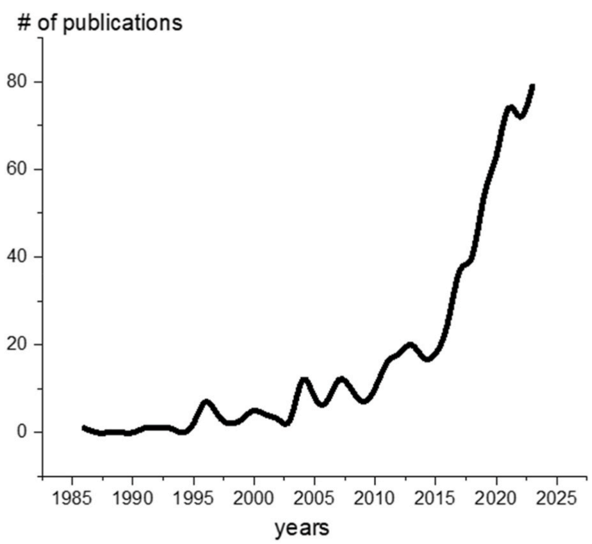


Fig. 1. Increasing of publications on air pollution-health-economy nexus.

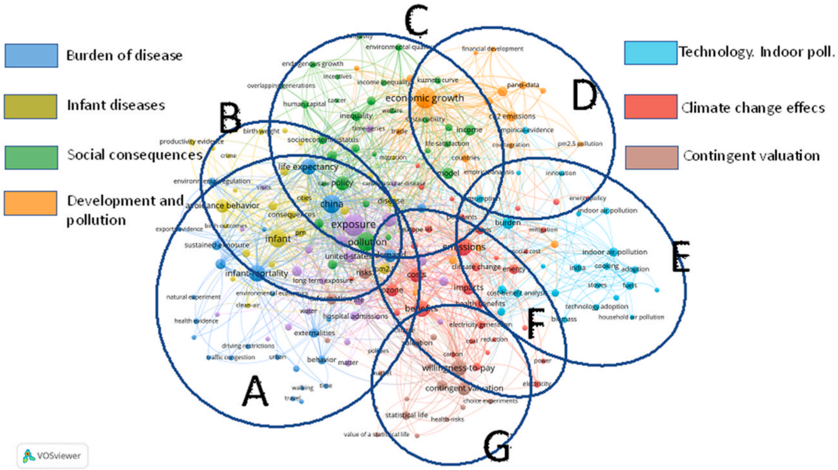


Fig. 2. Results of cluster analysis, based on co-occurrence of words and phrases.

application of biomass –based solution to decrease the air pollution can be considered as declining topics. Some questions (e.g. indoor pollution) are relatively intensively researched, but this problem is remains a relatively separated topics. The motor themes are the effect of climate change and the policy formation.

As a summary of the result of bibliometric survey it can be stated, that (1) the research of economic consequence's of air pollution caused disease burden in gaining in importance; (2) the majority of publications are focussing on some particular aspects of air pollution; (3) the in-depth and comprehensive economic analysis of the problem is in center of attention, but in this field there is just a

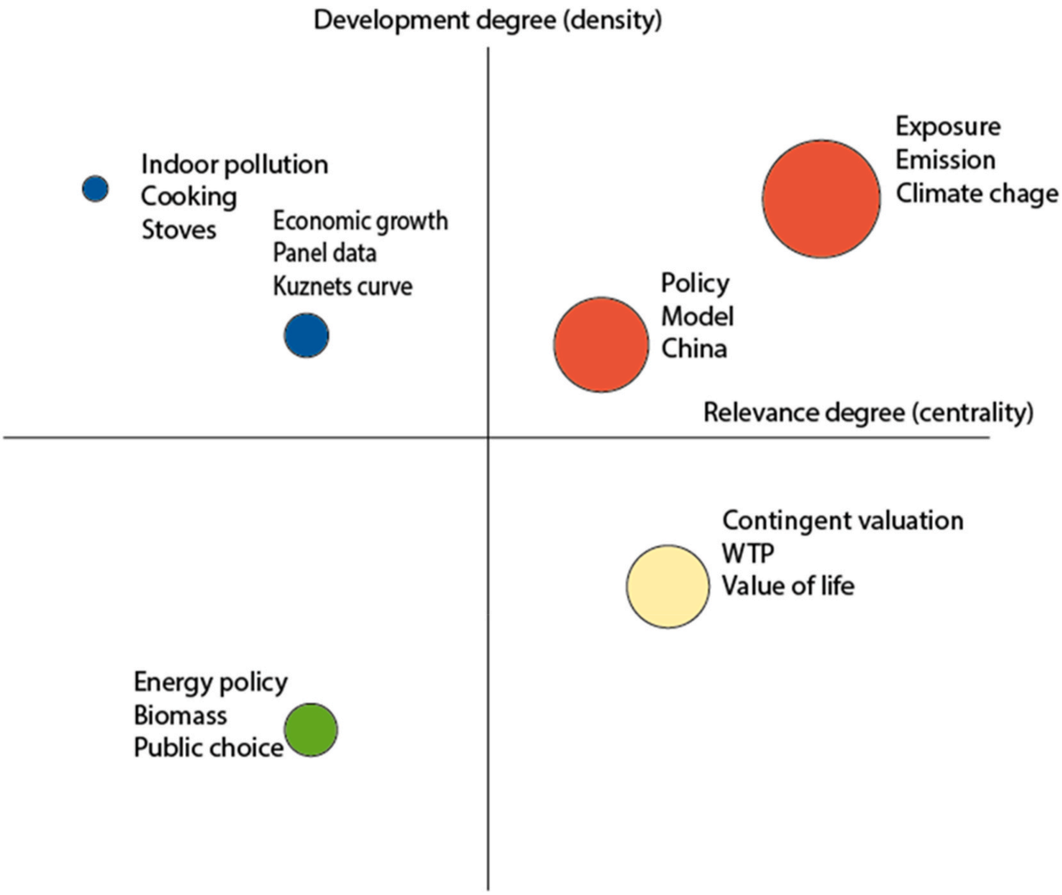


Fig. 3. Strategic map of air pollution and economy related publications.

relatively small number of publications.

1.3.2. Results in economic losses, caused by air pollution

As we have seen, the air pollution causes considerable health-related problems, that's why numerous attemts have been made to understand and quantifly these consequences. The systematic study of costs of illnesses begun nearly seven decades ago, when the developed societies ware facing with the consequences of increasing burden of diseases. In her seminal work Fein (1958) presents a coherent picture on economic consequences of mental illnesses [45]. Later on Klarman et al. (1968) presented calculations on direct and indirect medical care expenditures [46]. The basic idea of these papers is the systematic calculation of medical expenditures and the economic losses, caused by decreasing of living labor. In her synthetizing work, Rice (1965, 1967) offers a detailed list of methodological problems of such type of analysis [47,48]. The most important of these are as follows: statistical estimation problems of employment level, financial valuation of non-paid services (e.g. housewives' services), distorting role of transfers in payments and taxes, measurement of such intangible costs as pain, presence of multiple diseases, distribution of death within a given year, gaps in the statistical system just to name a few. All of these problems remained valid ones even in our days. Some academics even question of cost of illness calculations. E.g. In opinion of Shiell et al. (1987) "the COI [cost of illnesses] studies only confuse, mask and mislead" [49]. Their basic argument is that "*the economic epidemiologist has no role to play in the decision-making process*".

Apart from these –rather extreme –approaches, the demand for quantification of economic consequences of air-pollution caused health problems is increasing. This is an evolving process, the toosl of analysis show a continuous development. Some examples of estimations of economic burden of air pollution are summarised in Appendix A. Xu et al. reviewed the current state of research on health costs of air pollution. They analysed 52 relevant articles [50]. The majority of the articles were based on a statistical analysis of time series of air pollution and trends in pollution-related diseases. These methods were able to provide a rather static picture of the economic burden of air pollution-related diseases, but mostly ignored economic dynamics and the circular causality of socio-economic systems.

The goal of our study to present a relatively new, more comprehensive method for estimation of economic losses, caused by air pollution in a relatively modern manner, taking into consideration the complex circularities, characterising the national economies.

The novelty of the present research article lies in some key features: (1) it will be demonstrated how, in the era of big data, different datasets can be linked to provide a relatively sound basis for a complex analysis of health-economy; (2) a system dynamics model demonstrates long-term effects of air pollution on economic performance using the example of a rapidly developing East-Central European country.

On the basis of the results presented in this paper, researchers worldwide will be able to produce similar models, and policy-makers will have a robust decision-making tool for long-term socio-economic planning.

As a summary, the problem of air pollution and its health consequences is a much-debated topic that is at the centre of public and professional attention, but our knowledge of real socio-economic costs of air pollution is relatively limited. The present article is structured as follows: the introductory section provides a summary of current research on relationships between air pollution and population health, followed by a detailed description of the actual research methodology. The third section analyses and interprets the results as well as outlines the limitations of the study, identifying ways of further development.

2. Methodology and data

2.1. Conceptual framework

Bai et al. (2018) offer a wide-range comparative analysis of various methods of estimation of costs of air pollution [51]. In their opinion the static methods generally underestimate the cost of air pollution, and the sophisticated econometric models, based on the computable general equilibrium demand a considerable amount of information, which is hardly obtainable. As a consequence of these considerations, we have searched such a method, which is capable to handle the adverse, long term consequences of air pollution, and at the same time is based on a relatively low number of parameters. To estimate the effect of various diseases on economic performance of we have applied the logic of EPIC (Projecting the Economic Cost of Ill-Health) model of the WHO. Originally, this method was developed ot measure the economic consequences of tuberculosis but later on it was widely applied in various fields of diseases [52]. This approach has been widely applied to estimate the burden of a wide range of diseases [53–57].

The conceptual model for our research was the macroeconomic model of Solow and Swann [58]. The basic propositions of the model, in non-technical terms, are as follows: (1) the Total Factor Productivity in a given national economy depends on capital and labour. The function between these two factors and the new value created in the economy and measured by Gross Domestic Product (GDP), can be approximated by a modified version of the Cobb-Douglas production function [59]. (2) One part of the new value is consumption, one part of it is investment. If the value invested is greater than the consumption of fixed capital (depreciation, amortisation), and the number of persons employed does not decrease, then the value added production will increase. (3) If we have information on capital and labor, assuming that the market for goods input and output will be stable, the future development path of a given national economy can be predicted. This requires the use of a system dynamics approach, because, e.g. the loss of living labour due to disease in year t_{th} will not produce value added in year $t+1$st, and this loss will reduce investment in year $t+2$nd year.

This rather simple and robust approach offers a straightforward way to determine the income-generating capacity of capital and labour [60]. If we assume that environmental pollution-related health reduced the quantity and quality of the living labour force and at the same time diverts some material resources from productive activities, we can determine the economic losses in different years. This simple model is illustrated in Fig. 4. This logic is widely used in health economic calculations [61–63].

It is well known that the consequences of air pollution are long term, spanning electoral cycles and governments. This paper aims to estimate the long-term consequences of air-pollution, this is why we focused on long-term consequences. According to this approach, we did not take into consideration the adverse effects of the COVID-19 pandemic and the war between Russia and Ukraine because (1) these must be considered as part of the “erratic” behaviour of economies (Fig. 5), (2) after these setbacks, a relatively fast catch-up period can be expected [64].

2.2. Workflow and construction of database

The aim of the article is to present the long-term economic consequences of air pollution. This will also have wide-range spillover consequences. Modelling such a system requires the collection of four types of data: (1) data on demographic processes, (2) data on health consequences of air pollution; (3) data on the costs of treating non-communicable chronic diseases caused by air pollution; and (4) macro-economic data to integrate the information collected in points (1–3) into one conceptual system and model.

The workflow of research is shown in Fig. 6.

We have chosen the sources of data with utmost care. We applied such type of databases, which are (1) considered as a “gold standard” by the majority of researchers; (2) have a relatively stable, generally accepted quality assurance policy; (3) are updated on a regular base. The sources of data, their quality control system and a recent application of these data sources in the current literature are summarised in Table 1.

2.3. Demographic data

The first step was to model the expected population in Hungary. For this purpose, we used a triangulation approach to reduce bias from different algorithms using two software tools: the Avenir Health [73] and the DAPPS system [74]. Our results were compared with projections of the UN demographic section (UN, 2023).

2.4. Data on health consequences of environmental pollution

Establishing a global database on the prevalence and incidence of different diseases by risk factor by country had been a long-standing ambition of health scientists [75] but this became a reality only when information systems and mathematical modelling reached a level that allowed such a system to be built. The Global Burden of Disease [GBD] information system has been developed over the past three decades, and is now considered a pivotal point of international comparative epidemiologic research [76]. The system provides a means of determining the estimated effect of different risk factors (among other things environmental risks) on the incidence and prevalence of different diseases, attributable to air pollution. All this information was downloaded for the Hungarian population for different diseases attributable to air pollution, by age groups and sex. We used the data from this system as a starting point for determining the health consequences of environmental pollution. This approach is in line with the logic of similar studies that aim to determine the economic burden of different risk factors [77–79].

Environmental pollution causes two types of losses for the population: on the one hand, we can calculate the additional age- and gender-related mortality due to environmental burden, on the other hand, we have to take into consideration the deterioration in quality of life due to the deteriorating health of patients with chronic diseases. In the case of fatal diseases, years of life lost were defined as the difference between age at death and life expectancy. If the onset of the disease occurred before the official retirement age (currently 65 years for both sexes in Hungary), the ability of patients to work was “discounted” for the period between the onset of the disease and the official retirement age by disability weights for different diseases, as defined by the WHO (2020) using the methods published on the GBD website (2023). The theoretical and methodological considerations for the application of these health-policy indicators are well covered in the literature [80]. The most important relationship between different indicators of quality–adjusted life years is summarised in Fig. 7.

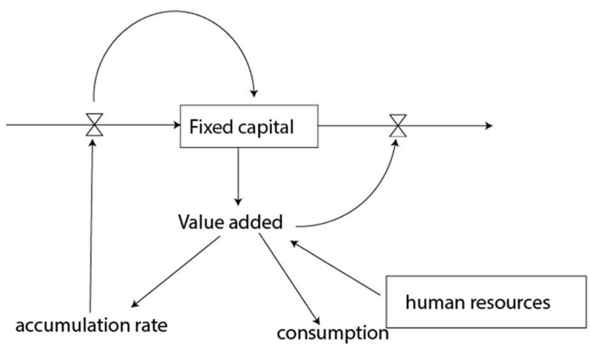


Fig. 4. The Solow-Swam model.

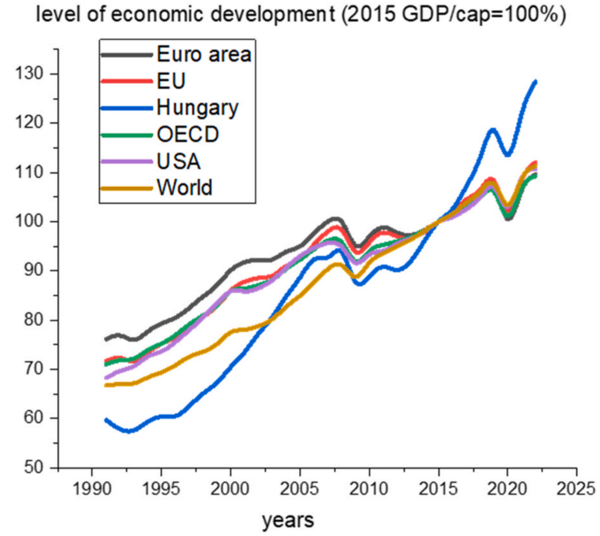


Fig. 5. Recovery of the world economy from the COVID-19 pandemy
Source: own calculations, based on World Bank databases

2.5. Calculating the cost of treating diseases

A crucial step in the determination of health care costs has been the calculation of treatment costs of different diseases. This was an extremely difficult task, as the current Hungarian health care monitoring system is not able to provide the necessary data [81]. Therefore, we applied a successive strategy to estimate the costs of treatment: (1) When data for Hungary were available in the literature, we adopted them, but converted the original data to 2019 price levels, taking into consideration the official rates of inflation of the Hungarian National Bank (MNB, 2013). (2) Where data for European countries were available, these data were converted to the corresponding Hungarian data, based on the comparative analysis of health care cost systems by Koechlin et al. [82]. If European data were not available, we used US data. On the basis of works by Sarnak and Anderson et al. [83,84] US data were converted to German data by a factor of 0.5. Data for estimating the cost of treating diseases were obtained from a search of the Web of Science database. The search term was TS=((“name of the disease”) AND (“medical cost*”)). Medical costs in Hungary were converted into USD using the official database of the Hungarian National Bank [85]. In cases where only medical costs (hospital treatment costs) were included, informal care costs were included with an additional value of 44%. This coefficient was based on data published by Brodszky et al. [86]. To be on the safe side, we checked our estimates on a sample of practicing managers in the Hungarian health care system. Five specialists were involved in the cost estimation, all of them worked as managers in different hospitals in Hungary, were aged between 26 and 42 years, and were participants of a special course jointly conducted by the Faculty of Health Sciences of Semmelweis University and the Faculty of Food Science of the Hungarian University of Agriculture and Applied Life Sciences. Data were estimated by personal interviews. The experts were shown our original estimates, and asked to estimate the “correct” value in their opinion. Data were processed using the Shelf R-package [87]. Cost-estimation was integrated into a module of the course. The Ethics Council of the Doctoral School of Economics and Regional Sciences of the Hungarian University of Agriculture and Life Sciences examined the potential ethical problems arising from this method of data collection and concluded that no ethical concerns arose, as there were no data that could involve confidential information or data that would fall under the General Data Protection Regulation.

2.6. Determination of macroeconomic losses

The next phase of research focused on estimating the macroeconomic losses from air pollution.

The starting point for the Solow-Swam model, which is based in the well-known Cobb-Douglas production function [59,88,89].

Both of these approaches apply a considerable number of assumptions. The Cobb-Douglas model has been intensively criticized since its publication [90]. Its most important assumptions are as follows: perfect competition, constant returns, infinite adaptation capacity of capital; constant elasticity of labor and capital; neutral technological and organisational development, the aggregate capital can be separately measured from capital [91]. Obviously, these assumptions seem to be rather obsolete, especially in the era of fourth industrial revolution [92], but due to its robustness, this approach seems to be applicable as a first approach for the determination the relative role of various production factors.

The Solow –Swann model applies a wide range of assumptions. Blair (2015) [93] have collected these on base of works of Acemoglu (2008) [94] and Solow (2008) [95]. In this opinion the basic assumptions are as follows: ”*constant depreciation, closed economy, constant return to scale, constant saving rate, diminishing marginal productivity, income is proportional to marginal productivity, full employment, free technology, homogenous households, no debt financing, no government, perfect competition, profit maximization, single commodity produced,*

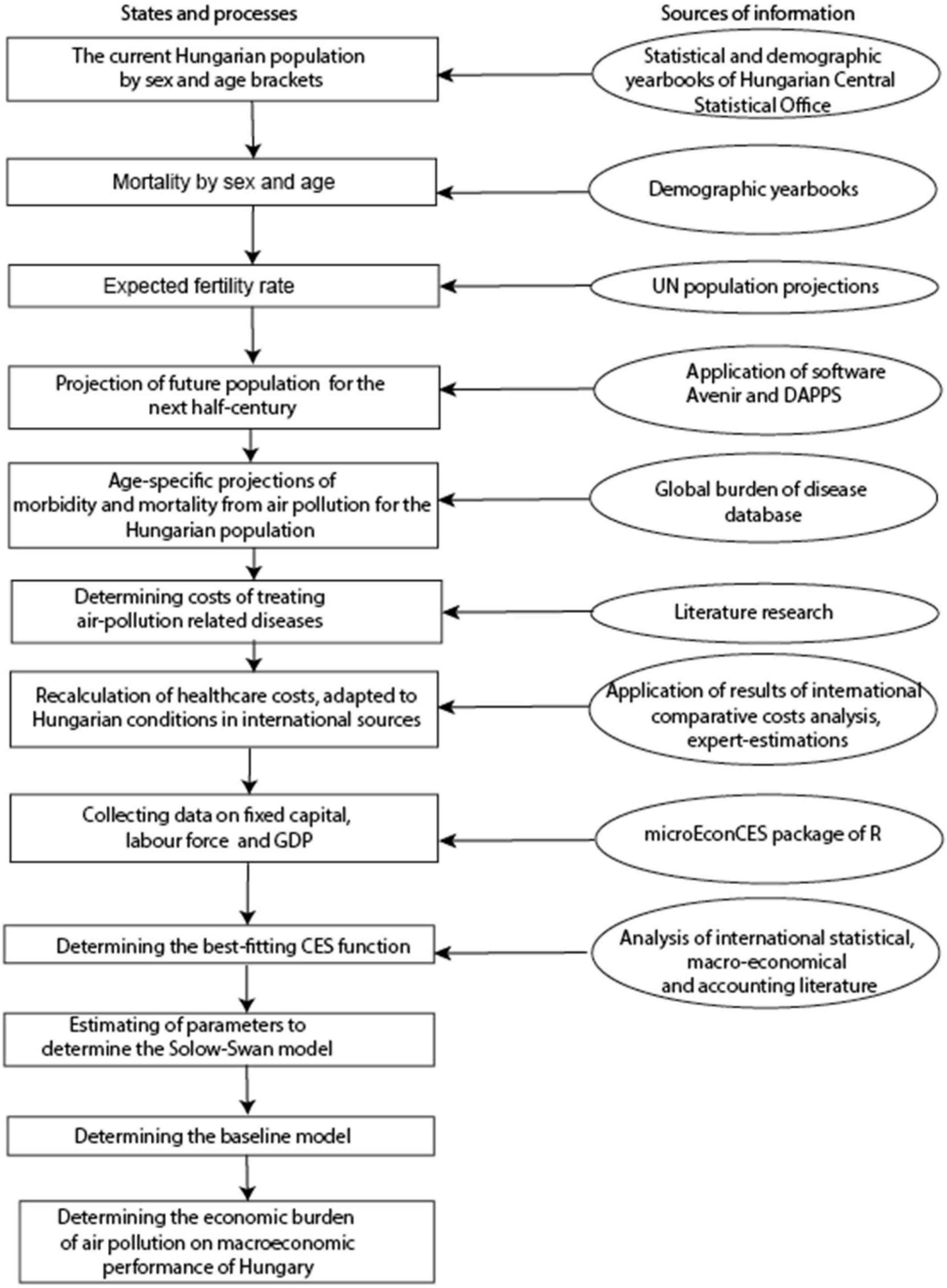


Fig. 6. Flowchart of investigations.

single economic sector". These fifteen assumptions highlight, that we have to apply this method with utmost care. Solow itself has known it, when he has stated in his world –famous article: "*All theory depends on assumptions which are not quite true. That is what makes it theory.*" [96]. In our opinion the robustness of this model make this approach as an applicable tool, but-of course-we have to be very conscious in the phase of interpretation of the results. Notwithstanding of its problems and weaknesses, the model is widely used. E.g. the Solow –Swann model is widely used in economic policy analysis [97,98] and health economic models [99,100].

Fitting this function requires some special algorithms, going far beyond the traditional regression technique, as there are at least

Table 1
The most important sources of data, their quality control systems and recent examples of their application.

Data	Data quality control system	Example of application
Demographic yearbook of Hungarian Central Statistical Office	Mag et al. (2011) [65]	Grosz et al. (2023) [66]
UN demography statistics	Reister et al. (2022) [67]	Lawson (2023) [68]
Penn World Tables	Henson (2017) [69]	Lee and Viale (2023) [70]
Global Burden of Diseases	Mikkelsen et al. (2015) [71]	Yeong et al. (2023) [72]

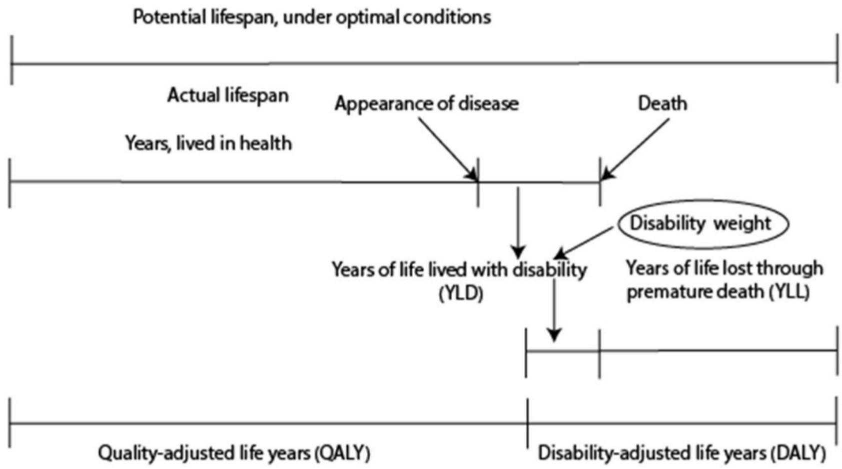


Fig. 7. The weighting mechanism for years of life lost due to disease.

four unknown parameters in the equation. In the last decades, rapid progress has been made in numerical methods to determine the parameters of this equation [101]. We used the micEconCES **R** package [102].

For the determination of the Cobb-Douglas function of TFP in Hungary, we used the Penn World Table data system, as this database offers a coherent estimation of the parameters needed for the calculations [103].

In determining model parameters, the depreciation was estimated at 3.5%, the ratio of investment from GDP at 24%. These parameters were calculated using the World Bank database [104].

2.7. Determination of the model

For our model, we applied some assumptions and conditions necessary to operationalize the theoretical construct. The most important of these are as follows.

- We assumed that if we are able to determine a long-run relationship between capital, labour and GDP on basis of historical data, it will be stable for the next half-century, too.
- We assumed that in-and output prices would increase in parallel. We therefore assumed that there would be no drastic changes in value relationship.
- We calculated with real values, not taking into consideration the effect of inflation in historical data.
- We did not take into consideration the potential in-or outward migration.
- We did not take into consideration some shock-type changes in the future (e.g. a new war in Central Europe).
- We assumed that the members of a given population group who die from air pollution would live in good health to the end of the working life (65 years). This means that the annual losses from early deaths from air pollution are projected to the year when members of the cohort leave the active working age.

For this simulation, we used a three-phase investigation.

- In the first phase, we defined the baseline (status quo) scenario, assuming constant processes and not taking into consideration the possible improvement in air pollution.
- In the second phase, we calculated the effect of loss of living labour, and compared it with the baseline scenario. In this way, we were able to determine the direct economic effect of air pollution on the value-added creation.
- In the third phase, we could evaluate the effect of additional funding for health care costs, so in this scenario we assumed that the monetary resources, allocated for the treatment of air pollution-related diseases could be converted into investments.
- In the fourth phase, we determined the effect of superposition of these two factors on GDP.

- In the fifth phase, we analysed the sensitivity of our model to changes in initial parameters.

Our model was n calculated using the Vensim simulation package [105].

3. Results

3.1. Demographic processes

All demographic prognoses show the same tendency: a decreasing population with increasing average age of it (Fig. 8). This tendency is in line with the demographic processes in other European countries.

Fig. 8 shows that in 50 years the population is expected to decline radically. This can be explained by both the decline in the number of people in each age group and an increase in the average age.

The relative importance of different air pollution-related diseases in different age groups is shown in Fig. 9.

Fig. 9 shows that, ischaemic heart disease predominates up to the age of 55. The incidence of COPD and cataract shows a gradual increase in each age group, reaching a peak at the oldest age. The incidence of stroke and lower respiratory diseases does not differ significantly between the age groups.

3.2. Costs of treatment for air-pollution-related diseases

An estimate of the costs of treating different diseases is given in Table 2, based on the estimation procedure described in section 2.3. A detailed list of sources on which the estimates are based is given in **Supplement 1**.

As shown in Table 2, air pollution affects the cardiovascular and respiratory systems most severely, so the costs of treating diseases of these organs and systems are high due to the high number of cases.

3.3. Forecasting the future development of the Hungarian economy

The main features of the economic development in Hungary over the past five decades are summarised in Fig. 10.

As illustrated in Fig. 10, labour force declined radically in the 1990s and then slightly in 2008, consistent with the changes in GDP over these periods.

Obviously, the Hungarian economic development can be characterised by a rather specific behaviour and strong cyclicality. A good example of this is the case of fixed capital formation (Fig. 11).

Despite the specific nature of economic development, we were able to identify a regression function between labour, capital and GDP that fits reasonably well:

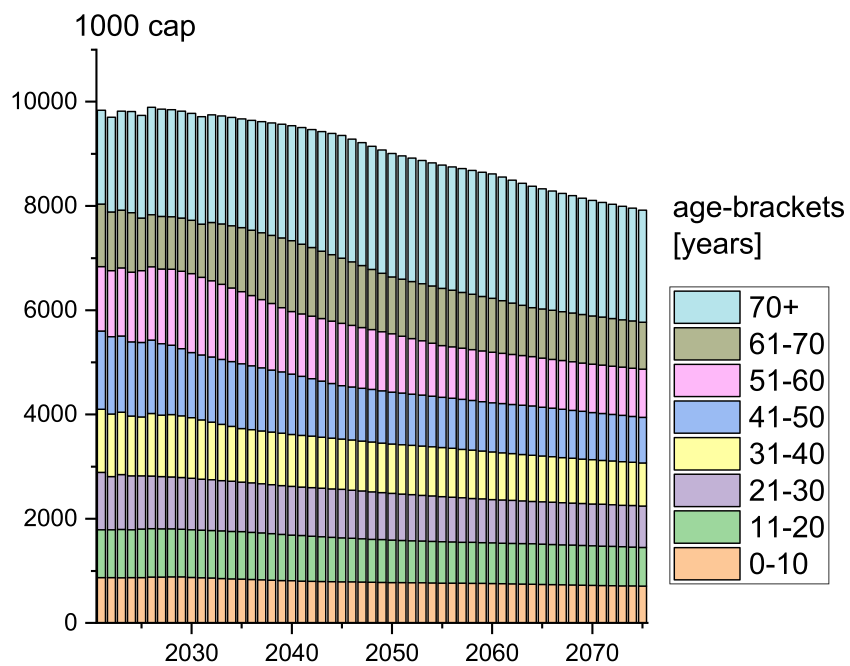


Fig. 8. The projected Hungarian population by age groups.

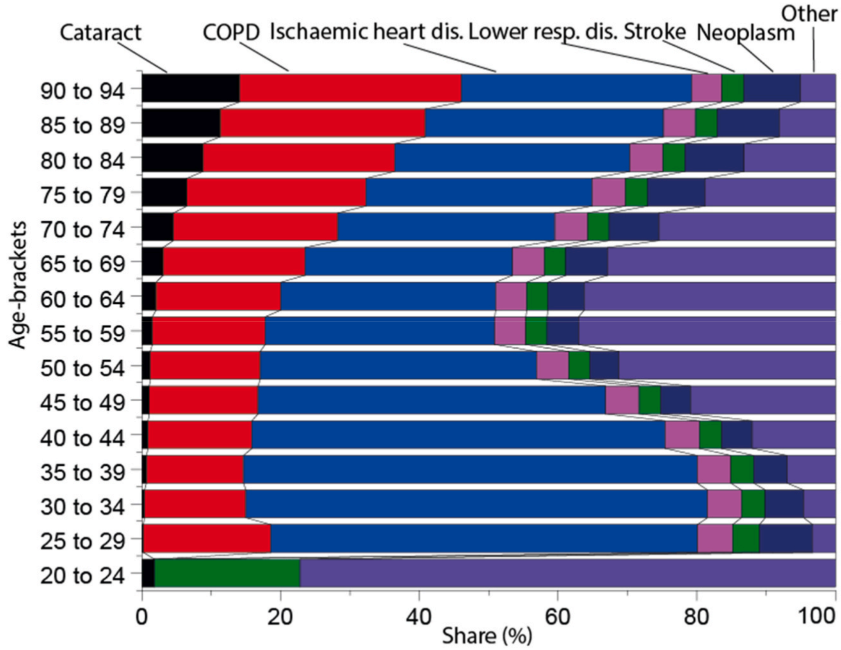


Fig. 9. Relative importance of different, air pollution-related diseases by age group.

Table 2
Estimated annual treatment costs of diseases.

Disease	Estimated annual treatment costs (USD/per capita/year)
Cardiovascular disease	3500
Cataract	100
Visual impairment	80
Chronic obstructive pulmonary disease	1000
Diabetes	450
Stroke	1200
Hypertensive heart disease	300
Ischaemic heart disease	1100
Chronic kidney disease	1800
Lower respiratory disease	200
Ischaemic Heart Disease (IHD)	2300
Non-rheumatic valvular heart disease	1500
Other cardiovascular and circulatory diseases	400
Tracheal, bronchus or lung cancer	15000

$$GDP = 2.179\left(0.281C^{1.455} + \left(0.829L^{1.455}\right)^{\frac{0.947}{1.454}}\right)_{R^2=0.946}$$

where.

C is the capital stock at constant 2017 national prices, and.

L is the number of persons employed.

As shown in Fig. 11, GDP is the new value added produced in Hungary in the given year, calculated on the basis of national accounts, expressed at constant 2017 national prices, in 2017 UDS values.

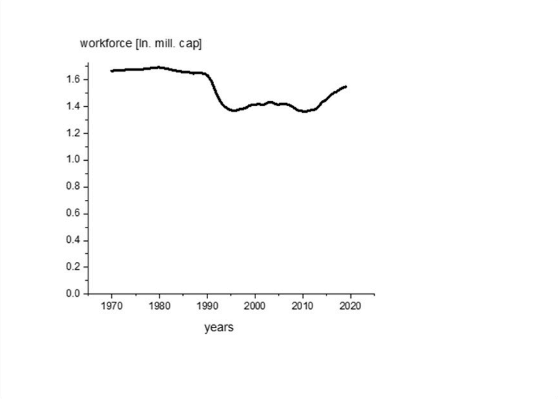
The estimated data and the actual GDP values are summarised in Fig. 12.

As Fig. 12 shows, GDP estimates for the period of 1970–2020 correspond fairly closely to the actual data.

On the basis of this estimate, we calculated a baseline scenario for economic development over the next half-century (Fig. 13).

In the final phase of the calculations, we determined the economic losses due to air pollution. We found that the most important factor in economic losses is the loss of human life in the working-age population. The annual number of deaths in this cohort is close to nearly 19,000. Due to the general ageing of the population, this number will decrease to 12,500 by the end of the projection period, 2073. The number of years lost from work due to premature death is 13.7. This will also be reduced, due to well-known social trends. Losses due to a decline in the quality of life of the working-age population account for about a quarter of the life years lost due to mortality. The total losses from air-pollution-related diseases are considerable, amounting to around 4 % of the annual GDP. We

10/A The workforce in Hungary	10/B The fixed capital and GDP in Hungary



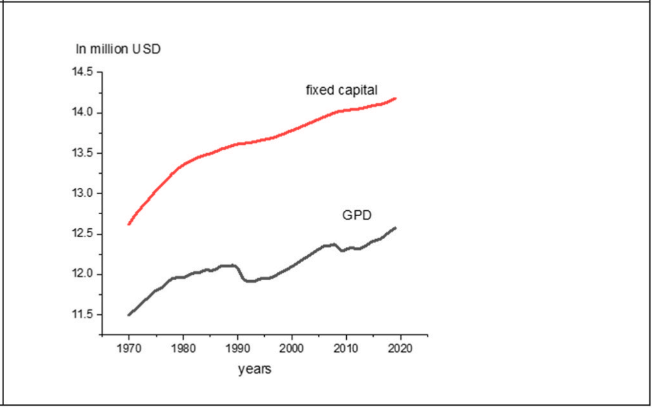
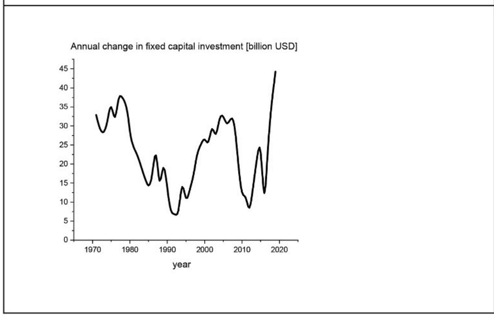
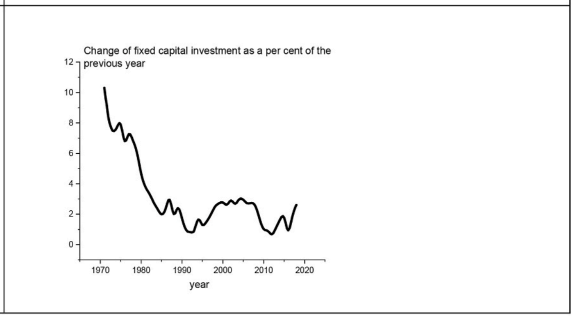


Fig. 10. The main features of Hungarian economic development from 1970 to 2019;
10/A The workforce in Hungary¸ **10/B** The fixed capital and GDP in Hungary.

11/A Annual change in fixed capital investment	11/B Relative annual change of fixed capital investment





11/C Cycles in fixed capital formation

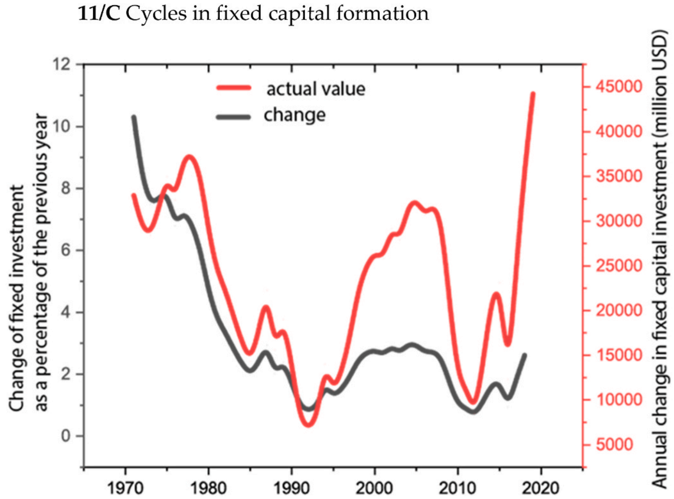


Fig. 11. The roller-coasters of Hungarian investment activity
11/A Annual change in fixed capital investment, **11/B** Relative annual change of fixed capital investment, **11/C** Cycles in fixed capital formation.

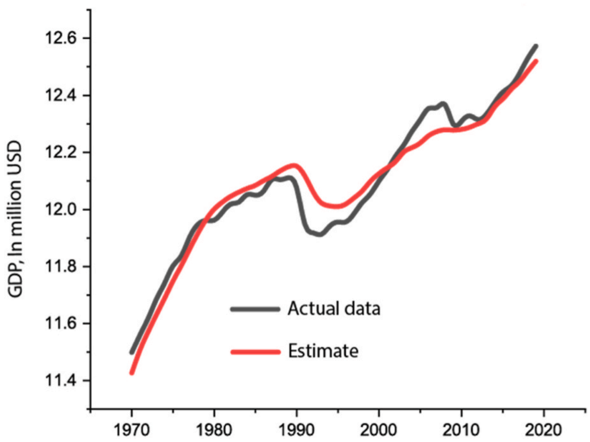


Fig. 12. Actual and estimated values of Hungarian GDP based on historical data.

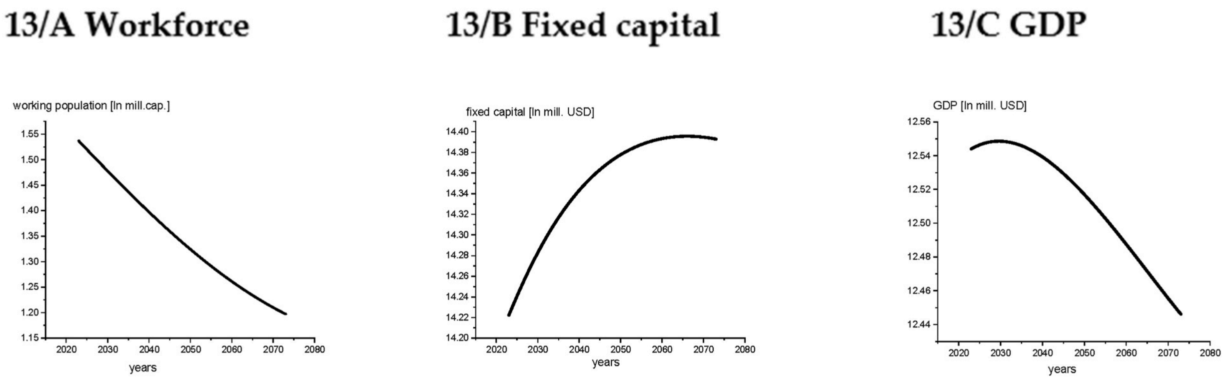


Fig. 13. The main features of Hungarian economic development, 13/A Workforce, 13/B Fixed capital, 13/C GDP.

estimate that this will rapidly rise to 9% of GDP by the end of the projection period (Fig. 14).

3.3.1. Economic losses due to increased healthcare costs

Losses caused by health care costs are much more lower by an order of magnitude. These costs will amount tp 0.9 % of the total GDP only by the end of the projection period. This implies that the total burden of diseases is approximately 4.2 % of GDP, rising to 9.9% % of GDP by the end of the projection period.

4. Discussion

The Hungarian population is ageing considerably. The population will decline considerably, and, without an increase in the number of people of retirement-age-the working-age population is expected to decline significantly. This implies that measures to improve the health of these cohorts, are of increasing importance for productivity. At the same time, we must also recognise that the absolute and relative population size of the older generation will increase quite rapidly in the coming decades. For this population group, health problems caused by air pollution are more frequent and more severe, and it can therefore be stated that, due to demographic changes in the number and structure of the Hungarian population, the problem of air pollution-related diseases will become more and more important.

Modelling the Hungarian economy is a rather difficult task because (1) fixed capital investment shows a high degree of cyclicity, depending on the political will of the ruling forces and market conjuncture; (2) the supply of living labour shows a decreasing tendency in the long-run, but interventions by different governments can considerably change this picture.

The rollercoaster of Hungarian investment cycles is well known and documented. In the 1980s, political will fuelled significant investment, in the decade of additional resources from the EU. A striking example of this has been the public work programme of the Hungarian government in power since 2010. This project has considerably increased employment, even if the quality of the additional labour force is rather heterogeneous. At the same time, we have been able to determine a relatively well-fitting function, describing the relation between the two key factors of production: capital and labour as well as the new value produced in the society in a given year. By comparing the fitted values to the actual ones, it is obvious that the estimated values are well fitted, except for the period of regime

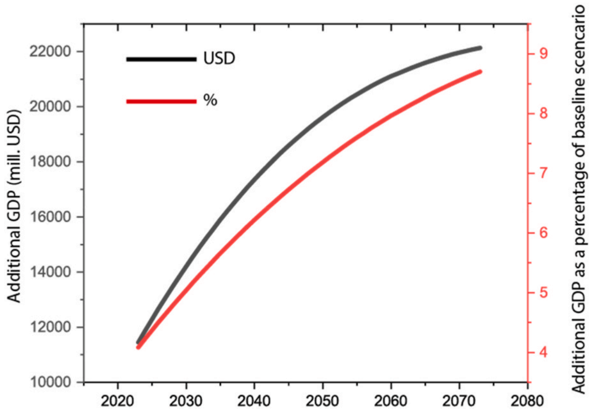


Fig. 14. Economic losses caused by premature death and declining productivity of working-age population.

change and the global economic crisis. These positive results suggest that this relatively stable relationship will be maintained over the next five decades.

Accepting this hypothesis, and projecting the future development of the Hungarian economy, we believe that the working-age population will continue to decline and that there will be a considerable accumulation of capital. The efficiency of capital utilisation will decline and GDP will grow only moderately over the next decade. GDP is expected to peak around 2030, after which a considerable decline in GDP will be the main feature of growth.

Air pollution can be considered an important economic burden, mainly due to the loss of living labour, but the value of material resources devoted to the treatment of air pollution-related diseases is also important. Both factors cause a considerable backdrop at a time when productive resources will be increasingly needed to sustain economic dynamism.

4.1. Sensitivity analysis of the model

The sensitivity analysis can be done in two ways: on one hand on logical, and on the another hand on the quantitative way. We have applied both approaches. However, in practice another factors shoul be taken into consideration. One of the most important assumption of our model is the acceptance of the demographic forecast of the UN, which is based on mathematical forecasting of the population on base of the population dynamics. There is a considerable similarity between the demographic tendencies (e.g. increasing of the average age of the population, decreasing number of children) in Hungary and another member-states of the EU [106,107]), but the forecasting of demographic and labour-force trends and structural changes in population of Hungary is an extremely difficult task, because (1) there is a considerable outbound-migration from Hungary to another countries. The intensity of this process is a function of (a) income and life-conditions differences between Hungary and the potential target-countries [108]; (b) labour force policies of the target countries (e.g. in the United Kingdom considerably modified and made more difficult the immigration of workers from the EU member states [109]; (2) there is a constant immigration to Hungary, mainly from countries, where the share of Hungarian ethnic minority is relatively important, e.g. Romania, Serbia and Ukraine [110]. This process is fuelled by Hungarian regulation of double citizenship program, which offers the possibility of getting Hungarian citizenship for ethnic Hungarians [111]. (d) EU-level and Hungarian regulation of illegal migration to Hungary, mainly from the third world countries [112]; (e) migration of guest workers, as a consequence of the increasing labour shortage [113]. (f) Hungarian immigrations policy to motivate the non-EU member to come to Hungary after buying “residency bonds”, issued by Hungary to contribute to the alleviation of the debt-crisis [114], (3) Success of integration programs of Roma minority, which can be currently characterized by an extremely high level of fertility, but low level of qualification [115,116].

As we have seen, the Codd-Douglas function and the Solow-Swann model both apply a wide range of assumptions. The validity of these is an important question. The most relevant factors, which may influence the results of analysis are as follows: (1) However we have tried to use the best availbalbe databases, there remained consideralbe biasses from point of view of reliability of input data. One of these is the estimation of the GDP, because these statistical data are not able to take into consideration the adverse consequences of tax avoidance systems. this is a general phenomenon. The text evasion and avoidance is a general phenomenon all over the world [117] both in developed [118], and in emerging countries [119,120]. The tax evasion problem is especially important in Hungary, where the text evasion rate is more than three times higher as in the neighbouring Austria and nearly tow times higher than in Slovakia [121]. (2) The cost of medical treatment show considerable differences in varioius countries. We have to take into consideration, that data, shown in Table should be considered juts indicative ones, because the exact analysis of healthcare costs in case of various diseases, based on a meta-analytical approach would beyond the scoep of the current study; (3) It is unknown, whether the coefficients of Cobb-Douglas function will be thrue in the era of fourth industrial revolution. It is highly probable, that the human capital will be a produciton factor of increasing importance, as opposed to the simple quantity of the living labour. (4) It is an open –ended question, whether Hungary will be a knowledge based economy, or its development will be built on traditional production factors [122]. If the former scenario will be realised, this will enhance the quality, and decrease the importance of the quantity of the workforce. Another very impornant way of development for Hungary is the intense utilisation of its natural resources for development of health and thermal tourism. The development of tourism [123], applying the favourable country-of-origin effect [124] could further enhance the importance of qualified living labour.

Beside the above problems, we have to take into consideration the effect of such specific events, like the long-range conflicts of a new cold war.

The quantitative sensitivity analysis was done by simulation methods. It became evident, that a minimal (e.g. 0.001%) change in constants of Cobb-Douglas function will forecast extreme, unrealistic values. The mortality and morbidity values of 45–55 years generation will be the second most important influencing factors of forecasting, followed by the morbidity and mortality of 55–65 years cohorts.

5. Conclusions

The aim of this article is twofold: on the one hand, to analyse the possibilities of quantifying economic losses from air pollution. It has been demonstrated that the current level of mathematical statistics and big data systems is capable of providing high quality, specific data for relatively sophisticated health economic modelling. The practical applicability of the Cobb-Douglass function has also been demonstrated, even for countries (e.g. Hungary) where economic development cannot be described by relatively simple functions. Interestingly, more complex estimations (e.g. taking technological progress into account or integrating population education into the model) have resulted in rather low levels of fit.

Based on economic projections for the next half-century, excluding the adverse effects of the COVID-19 pandemics and the war between Russia and Ukraine, it is obvious that the economic development prospects for Hungary are rather limited due to a declining working-age population and deteriorating capital efficiency. Under these conditions, improving the health of the population is not only a moral obligation, but also an important necessity.

The most important production losses are due to the early death of the working-age population. The second most important loss is due to a decline in the efficiency of the living labour force, resulting from a the deterioriation of the health status of the population. The significance of the capital loss from the cost of treating patients, suffering from air pollution-related diseases is relatively limited, but important. It is obvious that the additional costs of air pollution will be increasing. Currently, they reduce GDP by more than 4%, but in half a century, this will be close to 10%.

The applied model has been proven a simple and robust tool for estimation of economic losses, and the order of magnitude of them is the same, as in case of the similar models, prepared by different methods for anaother countries, summarised in Appendix B. Our work has highlighted the importance of exact model building and data collection. There remains a considerable work to better understand the air pollution-health – economy nexus, but as Arrow (1986) [125] has formulated [126]: „an unsatisfactory solution may be what is needed to provoke the needed information –gathering to produce a better one, while neglect is never productive".

5.1. *Further, potential ways of development of research*

The current study should be considered as a preliminary attempt to quantify the long-range consequences of air pollution. It is very important to emphasise, that there remain considerable un-answered questions. The most important of these are as follows: (1) Searching of new methods to better understand and estimate the relations between the production factors and value-added creation in the modern, postindustrial era [127,128]; (2) development of possibilities of more sophisticated macroeconomic models; (3) possibilities and application of artificial intelligence in in estimation and decreasing of the environmental burden [129]; (4) it is not enough to determine the adverse effects of air pollution, the research must support the development new ways for decreasing of air pollution [130]. This demands a holistic approach: the increasing of efficiency of the state-regulation must go hand in hand with enhancement of corporate social responsibility [131–133], wide range application of new materials and technologies [134–136], and development of logistical systems [137].

5.2. *Limitations*

At the end of the evaluation of our results, it should be stressed that the current model has considerable limitations and is therefore more of a decision-support tool and an economic evaluation of different alternative ways of development than the actual forecast of the economic development trajectory.

As we seen in the sensitivity analysis of the model, the estimated economic values considerably depend on a wide range of socio-economic factors, which are difficult to forecast. This uncertainty is especially characteristic in three fields: (1) the number of working population; (2) role of the living labour in era of fourth industrial revolution; and (3) the macroeconomic indicators, taking into consideration the long-range consequences of global conflict and crises.

Despite the relatively high number of theoretical assumptions, it can be concluded, that the model is useable, and can be considered as an applicable tool for political decision making in discussions on resource allocation. It is hard to argue with opinion of Finkensein and Corso (2003) [138]: "If nothing else, the cost of illness studies are a valuable tool for promoting attention toward a particular illness or condition and stimulating public debate".

Declarations

Author contribution statement

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Additional information

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CRediT authorship contribution statement

Zoltán Lakner: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **József Popp:** Data curation, Conceptualization. **Judit Oláh:** Data curation, Conceptualization. **Zoltán Zéman:** Data curation, Conceptualization. **Viktória Molnár:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Some examples of estimation of economic burden of health causes of air-pollution.

Source	Year	Method	Results
Bai et al. (2018) [58]	2018	Systematic review analysis of publications on air pollution costs in China	Air pollution related healthcare costs are equal with 3.5–5.9% of the GDP, calculated on base of static models. ON base of dynamic models this can be 6–9%.Welfare loss due to ozone and particulate matters increased from 22 to 122 billion USD between 1975 and 2005
Jaafar et al. [139]	2018	Systematic reviews on publications concerning the Asian countries	cost of air pollution related diseases, estimated by value of statistical life range between 180 and 2200 million USD, cost of illnesses methods estimate teh additional losses between 253 and 2900 million USD
Bayat et al., 2019 [140]	2019	Air pollution costs in Tehran, using the global exposure mortality model for Tehran combined by Value of Statistical life estimation	Total cost of air pollution was 3 billion USD in 2017
Kubatko and Kubatko [141]	2019	Direct and indirect costs of health effects caused by air pollution in Ukraine	Air pollution causes 0,7-1,3% loss in regional GDP
Michalski, 1964 [142]	1964	Empirical estimations on additional costs of air pollution on health.	Industrial countires >50 DM/per capita, 2.8 billion DM/year
Voss and Friedrich [143]	1994	Empirical estimations	Burden of pollution on public health in case of coal-based electricity production:0.2-2Euro/100 kWh
McCubbin and Delucchi [144]	1999	Contingent valuation, willingness to pay and expert estimation methods	Total costs of anthropogenic air pollution in US 54–672 billion USD (1991 value (

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Source	Year	Method	Results
Li et al. [145]	2016	Analyis of inhalable particulate matter (PM_{10}) and SO_2 in 74 cities of China, determinationof diseases on base of dose-response relatons various scenarios to economic consequences	Econmic loss is 1.63–2.32 % of GDP
Ridker [146]	1967	Linear model, evaluatio of losses by human capital method	Economic loss due to polluted air 80.2 billion USD (1958 USD value)
Zhang et al. [147]	2017	Province-level analysis of pollution data, estimation of diseases on base of literature data, calculation of medical costs and economic losses	Air pollution related costs are equal with 3.1 % of the GDP
Li et al. [148]	2004	Estimation of disease frequency on base of exposition-disease data, economic values are determined on base of willingness to payment method and VOSL methods for Shanghai	Total annual costs in case of various scenarios 94–395 million USD (1998 value)
Dechezleprêtre et al. (2020) [149]	2020	Determination of stochastic relationship between air pollution and economic activity on NUST 3 level of the EU	10% increase of $PM_{2,5}$ decrease the GDP by 1.1% on EU level

Appendix B

Costs of medical treatment according to different sources.

Name of disease	Country (country group)	Author	Year	Annual health treatment costs, in €, USD, or HUF
Myocarditis	SWE	Magnusson et al.	2020	57,118 €
Blindness and visual impairment	GER	Chuvarayan et al.	2020	8488 €
Blindness				1,9930
Cataract	HUN	Pónusz et al.	2021	199 €
Moderate to severe impairment				7121
Chronic Obstructive Pulmonary Disease (COPD)	GER	Wacker et al.	2016	2593–8924 €
	USA	Patel et al.	2018	6246 USD
	Twelve developed countries	Foo et al.	2016	
	Fr			3406 USD
	De			2255 USD
	IT			1172 USD
	ES			3570 USD
	RU			724 USD
Chronic Obstructive Pulmonary Disease (COPD)	EU	Yanev et al.	2006	2115 €
Chronic Obstructive Pulmonary Disease (COPD)	NO	Rehman et al. (2020re)		10,701
	Dk			9580
	DE			7847
	IT			7448
	Sw			7045
	El			2896
	BE			1963
	SR			2047
Asthma	International review	Puig et al.	2017	416-5317 USD
Lower respiratory infections	BG	Glagovska et al.	2010	1284 €
Diabetes mellitus	HU	Iski és Rurik	2014	133,000 HUF
Ischaemic heart disease	US	Menzin et al.	2008	2800 USD
Stroke	US	Wang	2014	20396-23256 USD
Subarachnoid haemorrhage	DE	Ridwan DE	2016	16030 €
Stroke	US	Dewiled et al.	2017	33147 USD
Stroke	NL	Strujis et al.	2006	25,7–35,000 USD in the first year, 5,7–8000 USD in subsequent years
Intercerebral haemorrage	DK	Porsdal and Boysen	2003	22,000 DK
Intracerebral haemorrhage	US	Shannon et al.	USA	52,417 USD
Hypertensive heart disease	HU	Gazsó et al.	2018	111,000 HUF
Hypertensive heart disease	HU	Iski és Rurik	2015	115,000 HUF
Non-rheumatic valvular heart disease	EU	Lip et al.	2017	450-3000 €
Atrial fibrillation and flutter	EU	Rahman et al.	2016	1010–3225 €
	DK	Johnsen et al.	2017	6422–8396€
Endocarditis	ES	Hereida-Rodriguez et al.	2018	15,281 €
Cardiovascular diseases	RS	Lukić	2014	335 €
Lower respiratory infections	EU	Oppong et al.	2010	23,88–116,47 €, the lowest value is the Hungarian one: 23,88 €

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Name of disease	Country (country group)	Author	Year	Annual health treatment costs, in €, USD, or HUF
Cataract	US	Zafar et al.	2019	228-342 €
Ischaemic stroke	DK	Jennum	2015	11,657 DK
Tracheal, bronchus and lung cancer	RU	Avxentyeva et al.	2018	2819 USD
Tracheal, bronchus and lung cancer	US	Tai et al.	2018	2819 USD
Chronic kidney disease	US	Coresh et al.	2003	3125 USD
Chronic kidney disease	UK	Kerr et al.	20112	78 GBP Dialysis: 26,835 GBP
Cardiovascular diseases	Europe/Hungary	Wilkins et al.	2017	3721.24 €
Ischaemic heart disease	Europe/Hungary	Wilkins et al.	2017	2227.9 €
Stroke	Europe/Hungary	Wilkins et al.	2017	10,234 €

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