HEALTHCARE DEMAND SIMULATION MODEL

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ABSTRACT

The aim of this paper is to study the influence of demography on the demand for healthcare services. The research is carried on in Wrocław Region (WR), Poland. We apply the system dynamic method and aging chain approach to simulate the number of individuals belonging to the respective age-gender cohorts. We consider such demographic descriptive parameters as birth and death rates, life expectancy and migration factors. Then, the discrete event simulation model is used to predict the annual demand for emergency hospital care, as registered at the hospitals located in the WR. The historical data on hospital admissions are drawn from National Health Fund regional branch. The input parameters describing the population are calculated based on historical and forecasted rates of primary demographic parameters, retrieved from various databases and official projections published by the Polish Central Statistical Office (CSO). The simulation predicts that between 2011 and 2020 the WR population will grow by 4.5% and the population aged 60+ will increase by 16.2%. Over the same period the number of arriving patients, compared to 2011, will be higher by 1.52%. Furthermore, the noticeable differences will be observed in the number of arrivals between particular hospitals.

INTRODUCTION

The proper estimation of the prospective demand for healthcare services is critical when supporting the decision planning processes at the regional or national level. The valid prediction of population demand for healthcare services can directly contribute to the improvement of people's access to health facilities. Information on the expected patients' arrivals to healthcare units is necessary when attempting to diagnose, correct, and improve the performance of the healthcare system. The credible assessment of future demand determines the optimal allocation of the available resources, which are usually insufficient to meet the population's needs. The initial assumptions on the predicted level of demand have to be made in order to evaluate the economic and/or clinical effectiveness of medical procedures, treatment therapies, and preventive and screening programs.

The forecasts of healthcare demand are essential at different management levels and in relation to different frames of reference. The predictions of demand may be formulated for different groups of healthcare services, such as primary, hospital, or post-hospital care. The estimations may be directed to the particular type of healthcare services (i.e., radiology services) or to the selected healthcare units (i.e., outpatient departments, hospital wards). Furthermore, they might be focused on the particular age-gender cohort (young women, elderly persons) or on the group of patients with the particular diagnosis (i.e., cardiac patients).

Arrival patterns are usually defined based on the historical data or on-site observations. These analyses are, however, focused on the supply aspect of the particular healthcare unit, and they fail when the challenge is to estimate a population's needs at the regional level and/or for the longer time horizon. The overall objectives of the regional health policy planning have a much broader context that requires the inclusion of the random and uncertain factors, and consideration of the constant changes observed in the demographic and health structures of the population. Because of these factors, the undesirable accumulation of demand may be observed despite the satisfactory average level of supply (calculated for the specific period). The incorrectly estimated demand may lead to erroneous assumptions when formulating the health policy, both for the particular supplier and at the regional or national level.

We attempt to develop a conceptual framework of demand simulation models, where the estimation of demand for healthcare services is based not only on the historically registered population needs but also on demographical, geographical, and temporal aspects. In this study, the relations between the volume of demand and the structure of population demography (age, gender, average life expectancy, birth rates), geographical aspects (allocation of health services providers, diversified population density across the region), and temporal aspects (daily, monthly, yearly arrival schedules) will be explored.

A DEMAND PERSPECTIVE OF HEALTHCARE SIMULATION MODELS

The computer simulation approach was selected because it is well suited to tackle problems related to healthcare

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management. The advantage of a simulation model is its ability to test any modification to fully understand the problem and to estimate the variability involved in the observed process. Furthermore, the healthcare system is a highly complex one and a simulation paradigm seems to be the best choice in this case.

The demand perspective may be taken as the main criterion in the classification of healthcare simulation models. Mielczarek (2014) divides the models into three basic groups: improvements, disease, and strategic, depending on the purpose of estimating the future demand.

The first group (improvements) of healthcare simulation models concentrates on the current work of units that provide the healthcare services. The models try to suggest improvements to the internal organisation of the unit assuming a certain level and structure of demand. The models are used for resource allocation, staff scheduling, admission planning, and managing patient flows in the healthcare units. They are concerned with formulating an overall diagnosis, identifying bottlenecks, and suggesting the changes that could improve the system's performance. The classical problem formulation is usually as follows: how to change the operation of the system to satisfy the output measures, given a certain level and characteristic of the demand?

Models from this group may concern:

- different clinical settings, such as operating theatres, outpatient clinics ambulatory care units, or diagnostic departments (Bowers, Mould 2004), (Persson, Persson 2009), (Testi, Tanfani & Torre 2007), (Rohleder et al. 2011);
- complex centers such as multi-unit hospitals, multi-facility outpatient centers (Cochran, Bharti 2006), (Matta, Patterson 2007);
- treatment processes such as radiation therapies, cataract surgeries, or local stroke care services (Werker et al. 2009), (Comas et al. 2008), (Bayer et al. 2010).

The goal of the models from group 2 (disease) is to study the cost-effectiveness or clinical effectiveness of medical procedures, medical treatments associated with clinical pathways, and prevention strategies or contemporary health trends. The demand is usually defined as a flow of patients classified by age, gender, and medical history, who are included in the simulation when they acquire the particular disease. The simulation is run within a sub-group of the whole population, pre-defined according to the goals of the study (Cooper et al. 2008), (Mar, Arrospide & Comas 2010), (Neovius et al. 2010).

Group 3 (strategic) models concentrate on the population needs and help the decision makers in implementing the capacity planning process at the regional or national level (Gupta et al. 2007), (Vissers, Adan & Dellaert 2007), (Desai et al. 2008). The models are also used to study the influence of the changes in demand on the healthcare units' standards of service. In these "what-if" type models, the "if" refers to the fluctuations in the demand intensity and patterns, and their impact on the system's operation.

This paper builds up on our previous study that reports on the use of combined simulation methods to support healthcare demand predictions (Mielczarek and Zabawa 2016a). In that paper we discussed the implementation of cohort modeling approach using the system dynamics method. The projections of long-term population evolutions were performed on the aggregated data and the analysis was focused on pre-specified age-gender cohorts. The demographic groups were described using parameters such as birth and death rates, life expectancy, and migration descriptors. This paper deploys the discrete event simulation model to study the demand for emergency hospital care. The model considers the demographic changes observed in the structure of the population inhabiting the region, the geographical factors that determine the selection of the preferred hospital, and the temporal factors that reflect the variability of the demand that is related to the season, month and time of the day.

SYSTEM DESCRIPTION

In Poland, the entry point for elective as well as emergency patients arriving to hospitals is an admission unit (AU) or a hospital emergency ward (EW), where the patient is qualified for hospital care and, if necessary, receives some medical treatment. A similar admission procedure applies to emergency patients without referral, emergency patients with referral, and elective patients. The AU provides consultancy and basic medical intervention and qualifies the patient for further hospital treatment. The EW performs an initial diagnosis, offers the medical treatment necessary to stabilize vital functions, and establishes the need for further hospital care. Both the AU and the EW may, after a consultancy, recommend the admission of the patient at the hospital ward or refer her/him for further treatment with the family doctor.

Our research is performed for two administrative districts of Lower Silesia, the fourth largest province in Poland. These two districts are called the Wrocław Region (WR) and encompass nine counties: the capital of Lower Silesia, Wrocław and eight other counties that are close to the capital. There are 17 AU/EW units located in the WR and they serve, in the first place, the inhabitants of the WR. The hospital care may, however, be also delivered to patients coming from other Polish provinces. At the same time, people living in the WR may receive medical treatments from the AUs and EWs located in other Polish sub-regions. The algorithm of forecasting the future amount of services delivered in the WR has to be therefore based not only on the demand coming from the WR population and covered by the WR hospitals but also on the demand generated by the inhabitants of the neighboring regions who arrive at one of the 17 AU/EW

units located in the region. Additionally, a certain number of patients inhabiting the WR may select the hospital outside the WR and this may result in a slight decrease in the demand covered by the WR hospitals.

MODEL CONSTRUCTION

Sub Models

The main model consists of two connected sub-models (Figure 1), each developed using a different simulation method. The discrete event (DES) sub-model of the WR healthcare emergency system was built using Rockwell Automation Technologies' Arena Simulation software, version 15.0. The model generates batches of emergency patients on a daily basis according to month-dependent arrival patterns. The second model was constructed using ExtendSim 9 by Imagine That Inc. to simulate demographic changes of the WR region. The sub-population model uses the system dynamics (SD) method and an aging chain approach to forecast the demographic changes that will be observed within the WR population over next 20 years (Mielczarek, Zabawa 2016b). The age-gender cohort simulation is performed using the deterministic approach, and hence there is no need to repeat the simulation runs. Only one replication per simulation experiment is performed and the output values describing the quantitative status of all age-gender cohorts, as registered in the subsequent years, are exported and kept in the external databases. The population data is then imported to the DES model to perform stochastic simulation for generating patient arrivals to the WR healthcare system.

More information about the aging chain population model may be found in Mielczarek and Zabawa (2016a).

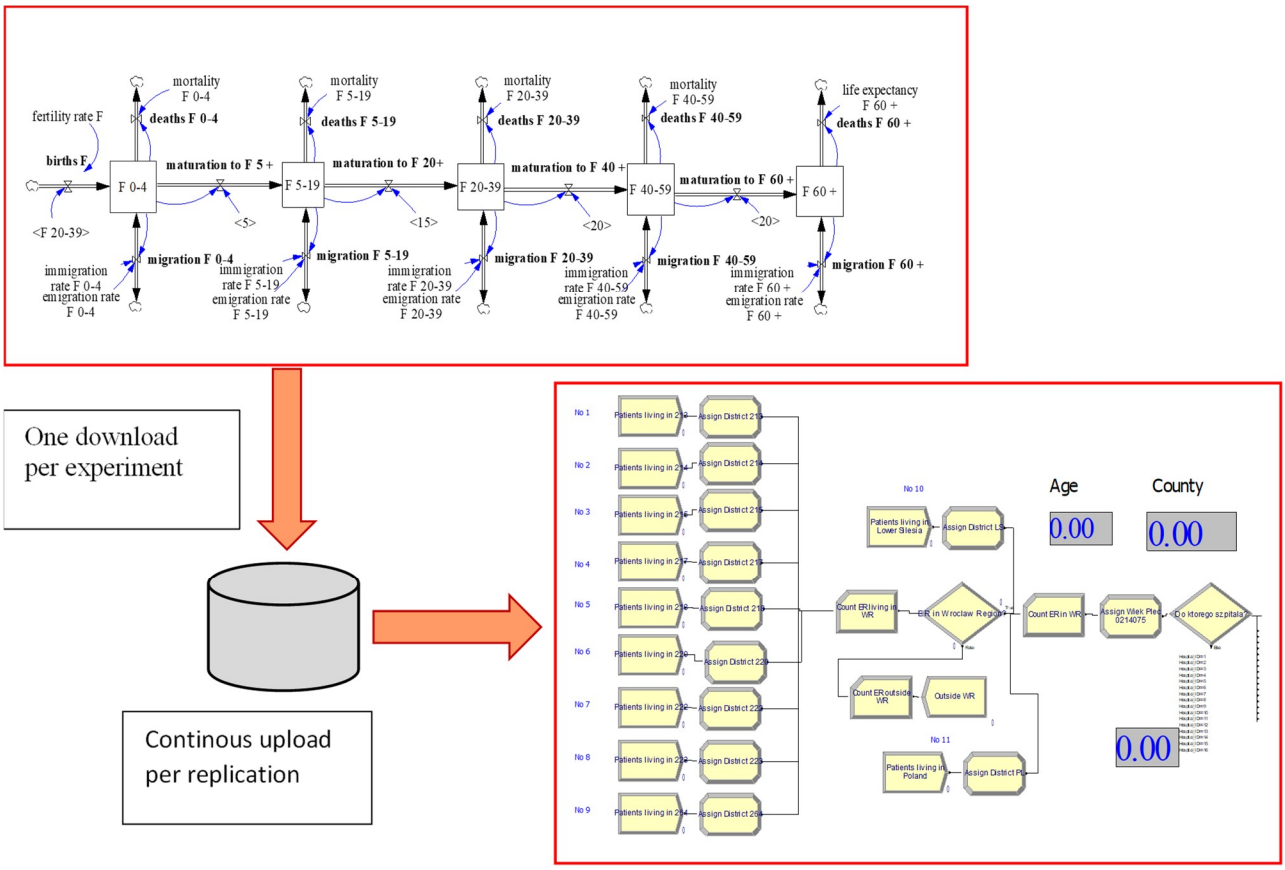

Figure1: Layout of the SD (upper) - DES (lower) model (fragments)

Simulation

The basic input flow is modeled by Arrivals Inflow 1 (Figure 2). The DES model samples the patients' arrivals from Poisson distributions with mean rates changing according to the county and the calendar month. The Inflow 1 describes the individuals whose place of residence is one of the counties of the WR and who express the need for hospital treatment. The majority of these calls will be served by the hospitals located in the WR; however, some patients will receive the treatment outside the region. This leakage is expressed by the Outflow (Figure 2) and represents the WR patients who decided to select the hospital outside the WR. The main Inflow is, however, expanded by the arrivals from other Lower Silesian counties (Arrivals Flow 2) or from the other Polish provinces (Arrivals Flow 3). The final flow of patients is then divided into 17 mini-flows that describe the demand registered in 17 hospitals located in the WR. Every admitted patient receives an individual

treatment in the particular AU/EW and the main diagnosis is formulated. The decision as to whether to send the patient home or start treatment at a hospital ward is usually made within few hours. After a consultation and the medical treatment, the patient is sent home or is referred to a hospital ward.

Simulation starts with the empty and unbiased system and lasts for 365 days. Every experiment is replicated 10 times without the warm-up period. A different stream of random numbers was used in each run. Output metrics include the total daily demand, i.e., the daily number of patients arriving at all WR hospitals, and annual demand as registered by each of the 17 hospitals located in the WR.

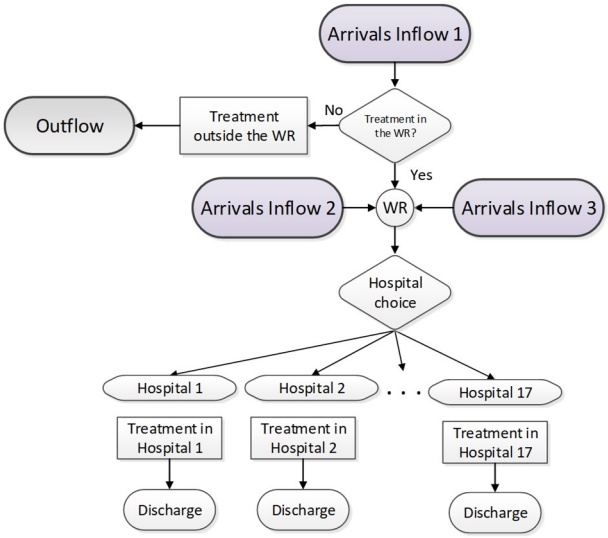

Figure 2: Flowchart of discrete event simulation model

RESULTS

Model Validation

To test the model, a historical validation was performed and a comparative analysis between the model output and actual performance of the system was carried out. Two output measures were calculated: the total annual number of patients as registered in each hospital in 2010 (Table 1) and the total monthly number of patients as registered in the WR (Table 2) in 2009 and 2010.

The results of simulation are consistent with the historical data. There are very small differences between historical and simulation data when comparing the total number of patients arriving at a particular hospital (Table 1), and the MPEs (Mean Percentage Errors) that relates to the whole region is also acceptable. The temporal distribution of patient arrivals exhibits, in some months, certain discrepancies compared to historical demand (Table 2); however, the averages calculated for each month for two validated years (2009 and 2010) are highly convergent. The values of MPEs indicate that the simulation model provides, on average, acceptable results for the estimation of the WR demand.

Table 1: Historical Validation – Total Annual Number of Patients as Registered in Each Hospital

Hospital no.	Historical data	Simulation data	MPE (%)
1	11 133	10 944	-1.7
2	2 919	2 830	-3.1
3	30 956	30 411	-1.8
4	18 385	17 918	-2.5
5	34 299	34 092	-0.6
6	6 066	5 857	-3.4
7	2 282	2 251	-1.3
8	12 317	12 849	4.3
9	6 826	6 816	-0.1
10	20 363	20 068	-1.4
11	13 188	12 748	-3.3
12	2 808	2 799	-0.3
13	27 888	27 242	-2.3
14	4 300	4 254	-1.1
15	1 218	1 194	-2.0
16	5 187	5 129	-1.1
17	3 950	3 921	-0.7
WR	204 085	201 324	**-1,35**

Table 2: Historical Validation – MPE (%) for Total Monthly Number of Patients as Registered in the WR

Month	2009	2010
January	-0.66%	-2.98%
February	0.52%	-4.25%
March	-0.45%	-7.54%
April	-0.40%	6.36%
May	-0.31%	-5.21%
June	0.36%	-15.12%
July	0.54%	-16.51%
August	1.65%	-5.52%
September	0.01%	4.00%
October	-0.45%	-9.46%
November	-0.54%	0.03%
December	0.32%	0.30%
Monthly average	**4.71%**	**0.36%**

Simulation Experiments

Under the base case scenario, we first run the SD sub-model to trace the evolution of the WR population from 2002 to 2020 (Figure 3 and 4). The next step is to evaluate the influence of the observed and predicted demographic trends on the forecast level of demand for hospital services exhibited by the WR population.

The simulation of the demographic changes begins in 2002 and runs through 2014 according to parameters extracted from the historical values, and then the SD sub-model is input with the coefficients calculated based on the demographic trends described in the official forecasts published by the Polish Government Population Council for 2014–2050 (Waligórska *et al*. 2014). The simulation

predicts that the WR population is gradually increasing and the population aging is an irreversible phenomenon. Between 2011 and 2020, the WR population is predicted to grow by 4.57%; however; over the same period the population aged 60+ will increase by as much as 16.20% (Figure 4).

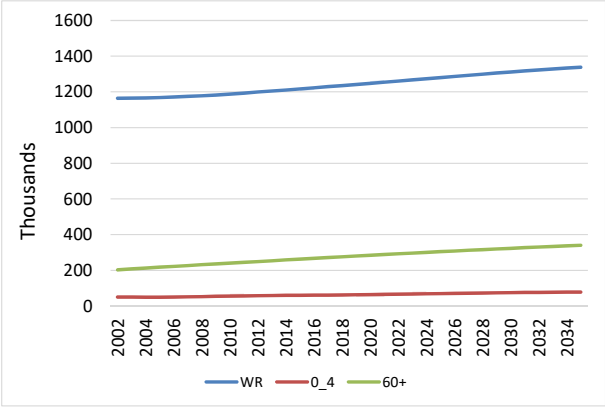

Figure 3: Projected status of the WR population

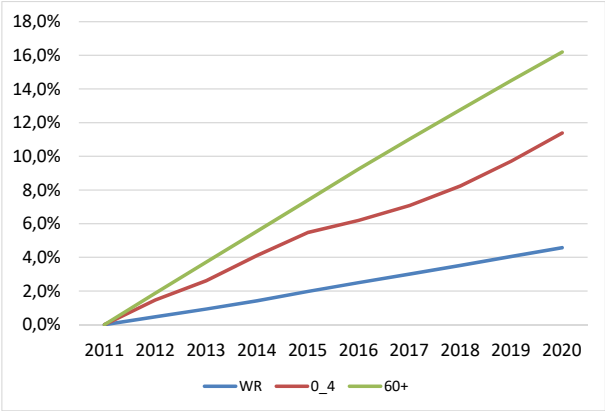

Figure 4: Projected percentage changes of the WR population in relation to 2011

The results of the aging chain simulation are then entered into the DES sub-model to observe the impact of population changes on the total number of patients arriving at the WR hospitals. As expected, demographic trends results in a noticeable growth, between 2011 and 2020, in the numbers of patients registering at the WR hospitals (Figure 5). The analysis of percentage changes of demand between 2011 and 2020, in relation to the quantities registered in 2011, shows that the level of demand will increase between 2011 and 2016. Next, it will remain stable to a year 2018, however between 2018 and 2020 the number of arriving patients will increase by as much as 1.52% compared to 2011 (Figure 5). It means that more than 3000 visits will be registered in the WR hospitals in 2020 relative to the year 2011.

Simulation experiments enable us to observe the demand directed to particular hospitals located in the WR. The detailed analysis shows that there are noticeable differences in the number of arrivals that the particular hospitals will register in the next few years (Figure 6). Although, between 2011 and 2020, the numbers of patients arriving at the WR hospitals will increase on average by about 1.52%, some hospitals will have to deal with the substantial growth in the number of arriving patients (i.e., Unit No 2: 2.54% and Unit No 12: 2.52%), while others will experience only a modest increase (i.e., Unit No 6: 0.53% and Unit No 11: 0.71%). This observation may have important implications for the future distributions of the resources on the regional level.

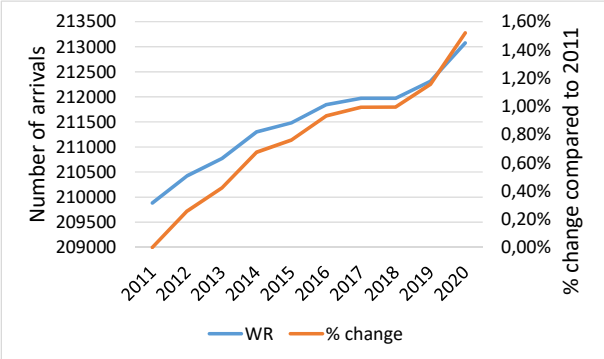

Figure 5: Predicted number of patients arriving at hospitals between 2011 and 2020 as a result of the simulated demographic changes in the WR population

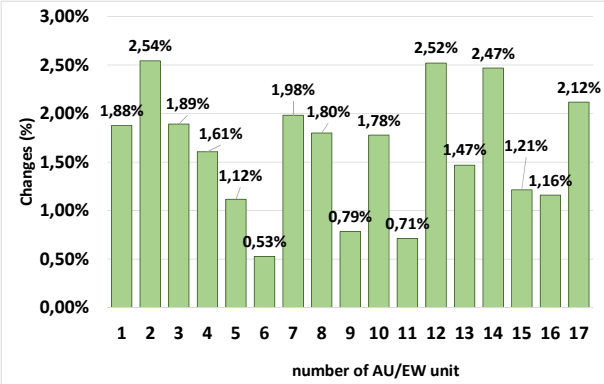

Figure 6: Percentage changes in the number of individuals arriving to the WR hospitals in 2020 compared to 2011

DISCUSSION AND CONCLUSSIONS

Healthcare policy planning at the regional level strongly relies on the proper and accurate estimation of future demand for services as expressed by the population inhabiting the area. The common approach is to focus on the past demand and the current levels of resource utilization (Cardoso *et.al.* 2012). Demographic trends have, however, a significant and stable effect on healthcare demand. The ongoing aging phenomenon, migrations, the declining children's population are the main reasons that the demand for the healthcare services changes gradually but continuously. The approach that neglects the influence of the demographic trends does not ensure an adequate identification of people's needs in the

future and may lead to an non optimal resource allocation. The health policy planning processes require more reliable forecasts of the intensity and the structure of the demand. This might improve the equity of access to health services across the region and adjust the future regional budget to the changing needs of people inhabiting the area.

The present work attempts to develop a conceptual framework of demand simulation models, where the estimation of demand for healthcare services is based not only on the historically registered population needs but also on demographical aspects. We suggest an original approach based on two connected simulation models: the system dynamics model to forecast the demographic changes of the WR population and the discrete simulation model to predict the hospital demand.

Our simulation experiments confirmed the strong impact of the ongoing demographic trends on the volume and geographical distribution of healthcare demand. The forecasts generated by the simulation model are convergent with official projections prepared by Polish Ministry of Health (Ministry of Health 2016). According to this analysis the intensity of the aging process in the region will be stronger than on the national scale and the demand for hospital beds will be increasing. When disregarding this influence, the unreliable forecasts may drive the health planning policies. We have also demonstrated the usefulness of integrating the SD and DES approaches to better explore the relationship between projections of population dynamics and forecasted demand for healthcare services. The complementary use of two simulation methods adds a new value to the process of predicting the future needs by considering a range of characteristics that describe both the population and the region. The demand for healthcare services is strongly driven by uncertain factors, and some of these factors are closely related to on-going changes in age-gender population profiles.

The discussion presented in this paper is a first step toward more comprehensive studies, and several research topics seem to be worth pursuing. First, the disaggregation rate of the aging chain into age-gender cohorts should be higher in both models to enable an even deeper analysis of the demographic trends and their impact on the healthcare demand. The same disaggregation pattern should be applied in the case of SD and DES sub-models to facilitate better communication and bilateral exchange of information. Next, we would like to extend the population model with some external/indirect incentives, such as economic growth, development of education or transportation infrastructure, and influence of the pro-demography policies. Lastly, the changes in population demography directly affect the epidemiological parameters and the risk factors. The changing risk factors modify the morbidity trends and thus influence the prevalence of diseases. The demand for healthcare services changes accordingly.

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