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THE IMPACT OF DEMOGRAPHIC TRENDS ON FUTURE HOSPITAL DEMAND BASED ON A HYBRID SIMULATION MODEL

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ABSTRACT

This study examines how changes in the age structure of Polish population inhabiting an administrative region, the Wrocław Region (WR), will affect the demand for healthcare services during the period 2016–2017. We constructed a hybrid simulation model that operates on two submodels. The system dynamics submodel simulates the evolution of population using an aging chain approach to forecast the number of individuals belonging to the respective age-gender cohorts. On the other hand, the discrete event submodel forecasts the number of patients in and number of treatments generated by the respective age-groups. We found that the effect of the WR population growth on the total healthcare demand will be small; however, it will have a larger impact on the number of elderly patients and the volume of more expensive services delivered in WR hospitals.

1 INTRODUCTION

In recent years, significant long-term demographic trends have been observed in the European population. The most important characteristics are the progressing decrease of the overall size of population and the constant increase of life expectancy, which in turn leads to the growing number of the elderly population. This phenomenon is also observed in Poland, where the total population between 2013 and 2016 decreased by 0.16% and the number of people older than 65 years increased by 11.12% (GUS 2017). In 2013, the elderly constituted 14.75% of the total population, and in 2016, this share grew up to 16.40%.

Demographic parameters are characterized by high variability and differ significantly between particular regions. These parameters are time and area dependent, and the inter-regional differences between particular communes, cities, and villages are sometimes significant. Our research is focused on one subregion of Lower Silesia, which is the fourth largest region extending to the south-west part of Poland, namely the Wrocław Region (WR). Between 2013 and 2016, the population of Lower Silesia shrank by 0.22% and the number of elderly people rose by 14.02%. During the same period, the population of WR increased by 1.43% and the share of people aged above 65 years increased by 13.52%.

The demographic transition directly affects different social spheres, including the volume and structure of healthcare demand for hospital inpatient services. As the number of elderly people increases, the demand for different categories of hospital services changes as well. Older people require more hospital services and their demand for certain types of treatments differ significantly from that of younger cohorts. Recently, the impact of aging on future hospital demand has been more intensively investigated in the scientific literature (Shunsuke Doi et al. 2017; Cardoso et al. 2012; Vrhovec and Tajnikar 2016). Although the close and direct relationship is uncontested, some authors (Strunk et al. 2006) suggest the effect may vary depending on medical conditions that more often occur among the elderly.

Simulation techniques have been extensively applied in healthcare research over the last decade. Simulation methods serve as a useful tool for forecasting the demographic population evolutions. The complexity of healthcare systems has urged researchers to look for tools that would provide a holistic insight into the systems, while preserving the unique and well-tested features of different simulation techniques, in particular, the ability to model quantitative as well as qualitative aspects, consider deterministic as well as stochastic variability, and use a static as well as dynamic approach toward the system description.

Population projections may be performed with different simulation paradigms and integrated with healthcare demand modeling. The overall goal of this study is to develop a conceptual framework of demand simulation models, which can be applied at the regional level of the healthcare system. We decided to combine two simulation methods − system dynamics (SD) and discrete-event simulation (DES) − to perform a hybrid simulation that would allow alignment of short-term demographic forecasts with health policy models to predict the future demand for healthcare services at the regional level. The dictionary (Cambridge University Press 2011) defines a "hybrid" as something that is a combination of two different things, so it has qualities relating to both of them. Extending this definition − a hybrid model integrates methods, types, constructs etc. hitherto occurring independently and the reason to use a hybrid model is a desire to get benefits unavailable when using the components separately. According to Arisha and Rashwan (2016), hybrid approaches are becoming increasingly popular in healthcare research, particularly to facilitate decision-making at the regional/community level.

Attempts to integrate SD and DES approaches have already been made by several researchers (Chahal and Eldabi 2008; Zulkepli et al. 2012; Chahal et al. 2013). These authors found that the hybrid model may provide more efficient support for decision-making in healthcare compared to simulation methods in isolation. More recently, Djitog et al. (2018) presented a framework for multi-paradigm simulation of healthcare systems that allows different aspects of the same system to be modeled using different paradigms. The authors discussed the idea of the live transmission of information between simulation models running in different perspectives. Our work fits well with the proposed framework. We focus on the mechanism that enables the outputs of one simulation model to affect the input parameters of the other model.

This study presents the results of the series of experiments that were conducted to analyze the effects of the predicted demographic changes on future demand for hospital services. We outline the overall idea of the hybrid model and discuss how changes in the age-gender distribution of the WR population will influence the future use of hospital services in the region. We keep all other factors constant and concentrate on a 15-year horizon. However, we also pose some inquiries for a somewhat distant future.

The remainder of the paper is organized as follows. Section 2 provides background information on healthcare demand modeling. Section 3 presents the data and methodology. Section 4 discusses the features of the experiment and the analysis results. Finally, Section 5 presents the discussion and conclusions.

2 DEMOGRAPHIC SIMULATION – LITERATURE BACKGROUND

The most common approach for modeling demographic trends is to use census data published by national statistical units or global organizations such as the World Bank or the United Nations. Historical data are usually very detailed and describe the share of population in different cross-sectional, age-gender groups, for the past several years. Moreover, the exact values of basic demographic parameters such as fertility rates, life expectancy, death rates, and migration ratios can be obtained accordingly.

When the research aims to investigate the future demographic trends, it becomes necessary to incorporate not only historical but also the projected values of demographic parameters. Time series modeling techniques may be adopted to extrapolate fertility, mortality, and immigration rates many years into the future (Lutz et al. 2001; Tian and Zhao 2016). Assuming that basic demographic parameters describe the uncertainty that drives the changes observed in population trends, stochastic simulation may be applied to predict the demographic trends. Simulation models are fast and reliable, and their usefulness in understanding the dynamics of population has been demonstrated in past decades in numerous studies.

A well-known simulation methodology that offers a strategic perspective on demographic phenomena is system dynamics. The SD method was applied by Eberlein and Thompson (2013), who developed and described the continuous cohorting approach, and suggested that it could be applied to any population for which true chronological aging is the best approximation to behavior. Barber and Lopez-Valcarcel (2010) used an SD submodel to simulate demographic changes for forecasting the demand for medical specialties. Ansah et al. (2014) developed an SD model to investigate the relationship between age-gender profiles and the demand for long-term care services; the population of interest were older patients who required human assistance. The SD method has also been applied by Ng et al. (2011) to model the demand for hospital services based on three main population groups: 0 to 14, 15 to 64, and 65 and above.

Demographic processes have also been successfully modeled with discrete simulations. Singh and Ahn (2017) incorporated all the major demographic parameters and applied agent-based simulation (ABS) to study the dynamics of fertility of population. Discrete event simulation (DES) was used by Olsson and Hössjer (2015) to simulate demographics and DNA for an age-structured population in which age class sizes fluctuate stochastically.

Another well-known simulation methodology that offers an alternative perspective on demographic phenomena is the Monte Carlo (MC) method. Tian and Zhao (2016) used MC iterative simulations to obtain the distribution of population in order to analyze the financial sustainability of the basic pension system in China. A similar approach was suggested by Onggo (2008), who applied microsimulation with random sampling in the demographic analysis. MC sampling was used by Shunsuke et al. (2017) to estimate the balance between supply and demand of healthcare services taking into account the concentration of elderly persons and the geographic accessibility of healthcare institutions.

The simulation approaches differ significantly. The random-sampling technique simulates a range of potential scenarios, each with an assigned probability of occurrence, and produces forecasts, usually in the form of relevant means, probabilities, and a dispersion of results around an expected value. The SD is a deterministic approach that does not provide accurate forecasts; rather, it aims to analyze behavior patterns over time. Discrete models (DES and ABS) simulate processes over time and follow individual dynamic objects (called *entities* or *agents*) that interact with the system's resources and with themselves. The main advantage of discrete simulation is its ability to relate risks, activities, and interventions with patients who are guided by their own will, have their own individual assessments, and may behave unpredictably.

3 STUDY DATA AND METHODS

3.1 Population Estimates

Our study requires three distinct types of data: age-gender specific population data, age-gender specific hospital arrival data, and projections of the WR population for each year during the projection period.

The data describing the WR population were collected from the Polish Central Statistical Office (GUS 2017) for the period 1999 − 2015, separately for 36 age-gender cohorts (Figure 1). The following descriptive parameters were calculated based on values extracted from GUS files: population size, fertility rates, mortality rates, net migration, and life expectancy. Female (male) fertility rates are obtained by dividing the total number of girls (boys) aged 0–4 by the total number of females from eight groups representing the childbearing age, for each historical year. Mortality rates are calculated by dividing the number of recorded deaths for a particular age-gender group with the total number of people belonging to that group. Migration describes the net total internal and international immigrations and emigrations. Life expectancy is used only for the two oldest groups (85+; male and female).

3.2 Hospital Demand

The data describing the 2010 historical demand for hospital care, as registered in 17 hospitals located in WR (Figure 2), were obtained from the regional branch of the National Health Fund (NHF).

The WR hospitals serve the inhabitants of WR as well as patients from other Lower Silesia subregions and citizens from other Polish provinces. In Poland, a patient can freely select any hospital in which she/he would like to be treated. Therefore, people living in WR may receive medical treatments from hospitals situated in WR as well as from those located in other Polish subregions. The basic datasets included information on 183,517 admissions registered in 2010 in 17 hospitals located in WR.

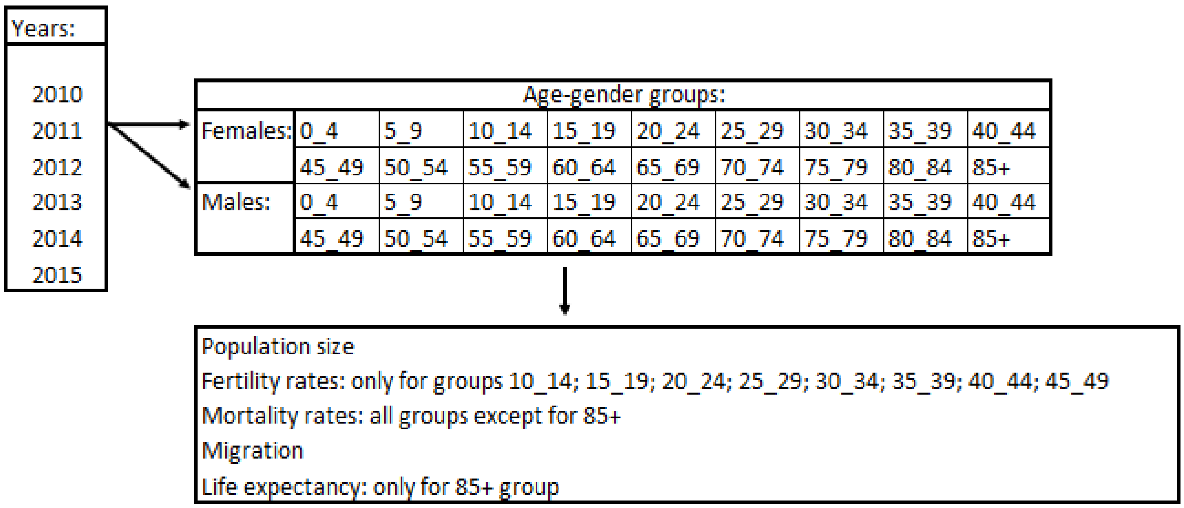

Figure 1: The WR population parameters calculated based on GUS files.

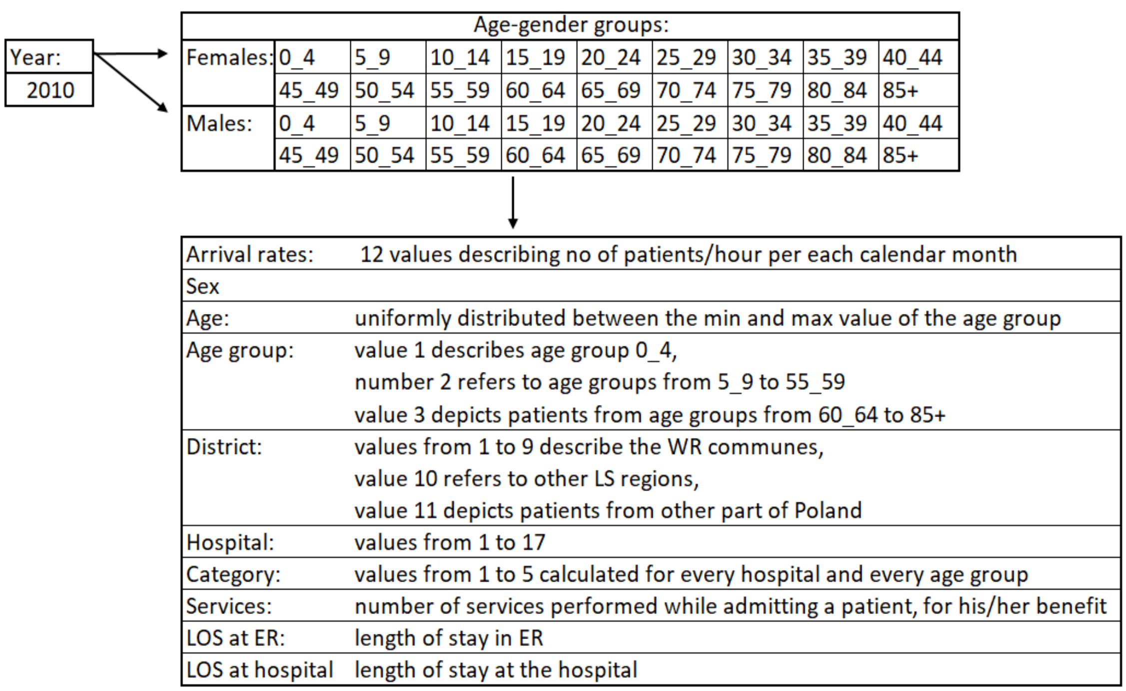

Figure 2: Hospital arrival data collected from the National Health Fund.

Every admitted patient receives an individual treatment described by a certain number of different services. The summary cost of all services provided to the patient determines the patient's *category*. A higher number of the *category* implies that the patient's treatment is more expensive.

3.3 Demographic Forecasts

The demographic scenarios developed by scientific institutes are based on the mathematical projection methodology and speculate the behavior of basic demographic parameters. In our study, we applied four variants of demographic forecasts based on the official calculations developed by the Polish Government Population Council for 2014–2050 (Waligórska et al. 2014). The basic demographic coefficients, including the fertility rate and mortality rate, are predicted to change alternatively according to one of the four possible trends: very high, high, medium, and low (see Table 1). On the other hand, migration and life expectancy are described by three possible trends: high, medium, and low. The Polish Government Council predicts that some trends have a higher probability of occurrence than the others. According to the guidelines outlined in the document, we have formulated four scenarios of the possible demographic changes of WR population (see Table 2). Among the four variants, Scenario 2 is considered as the most probable one.

Table 1: Forecasted trends for basic demographic parameters.

Parameter	Trend
fertility rate	very high, high, medium, low
mortality rate	very high, high, medium, low
life expectancy	high, medium, low
migration	high, medium, low

Table 2: Four scenarios of the possible demographic changes of WR population.

Scenario	Fertility rate	Mortality rate	Life expectancy	Migration
No 1	Low	Low	High	Medium
No 2	**Medium**	**Medium**	**Medium**	**Medium**
No 3	High	Medium	Medium	Medium
No 4	Very high	Very high	Low	Medium

3.4 Simulation Methods

We applied two simulation methods to build the hybrid model. The first submodel simulates demographic changes in WR using SD and the aging chain approach. The detailed description of our methodology is presented in (Mielczarek and Zabawa 2018; Zabawa et al. 2018).

The SD demographic model consists of a series of *stocks* that represent age-gender cohorts of female/male belonging to similar age groups. There are 36 main cohorts (0–4, 5–9, 10–14, 15–19, 20–24, 25–29, 30–34, 35–39, 40–44, 45–49, 50–54, 55–59, 60–64, 65–69, 70–74, 75–79, 80–84, 85–105): 18 female and 18 male cohorts. When an individual is born, she/he immediately becomes a member of the youngest cohort. After five years, a person grows up and is transferred to the older cohort. The maturation continues along the aging chain and, after the lifetime, an individual becomes the member of the oldest cohort. The *flows* in the demographic SD model are used to represent the following: birth (concerns only the youngest cohort, that is, the cohort starting with the age zero); maturation (a person leaves the previous cohort and enters the next one when the maximum age, as defined for the younger cohort, is reached); and immigration (the sources for immigration are irrelevant here). A person ceases to be a member of the cohort when she/he dies, is old enough to become a member of the older cohort or emigrates (the target for emigration is irrelevant here).

In order to obtain smooth adjustments of the sizes of age-gender cohorts, every main cohort in our model is divided into a number of *elementary* cohorts (Figure 3).

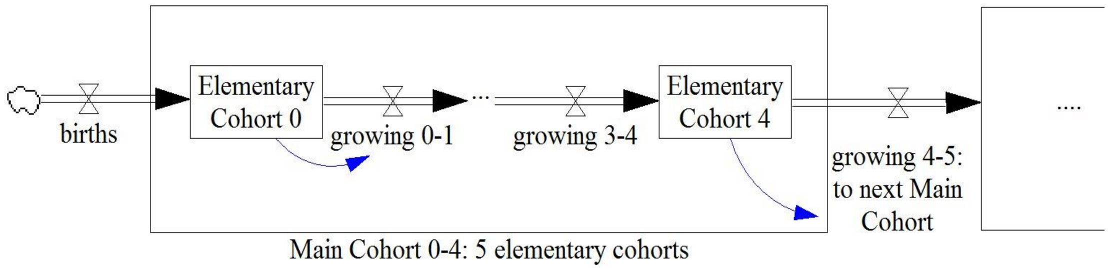

Figure 3: The illustration of the SD model structure.

The DES submodel simulates the demand for hospital services in WR (see Figure 4). The main input arrival flow (Inflow 1) describes people living in WR who require hospital treatment. The majority of these people arrive at WR hospitals; however, some patients receive treatment at hospitals located outside WR (Outflow). The main demand flow is increased by two additional flows of patients coming from other Lower Silesia regions (Arrival Inflow 2) and from other Polish provinces (Arrival Inflow 3).

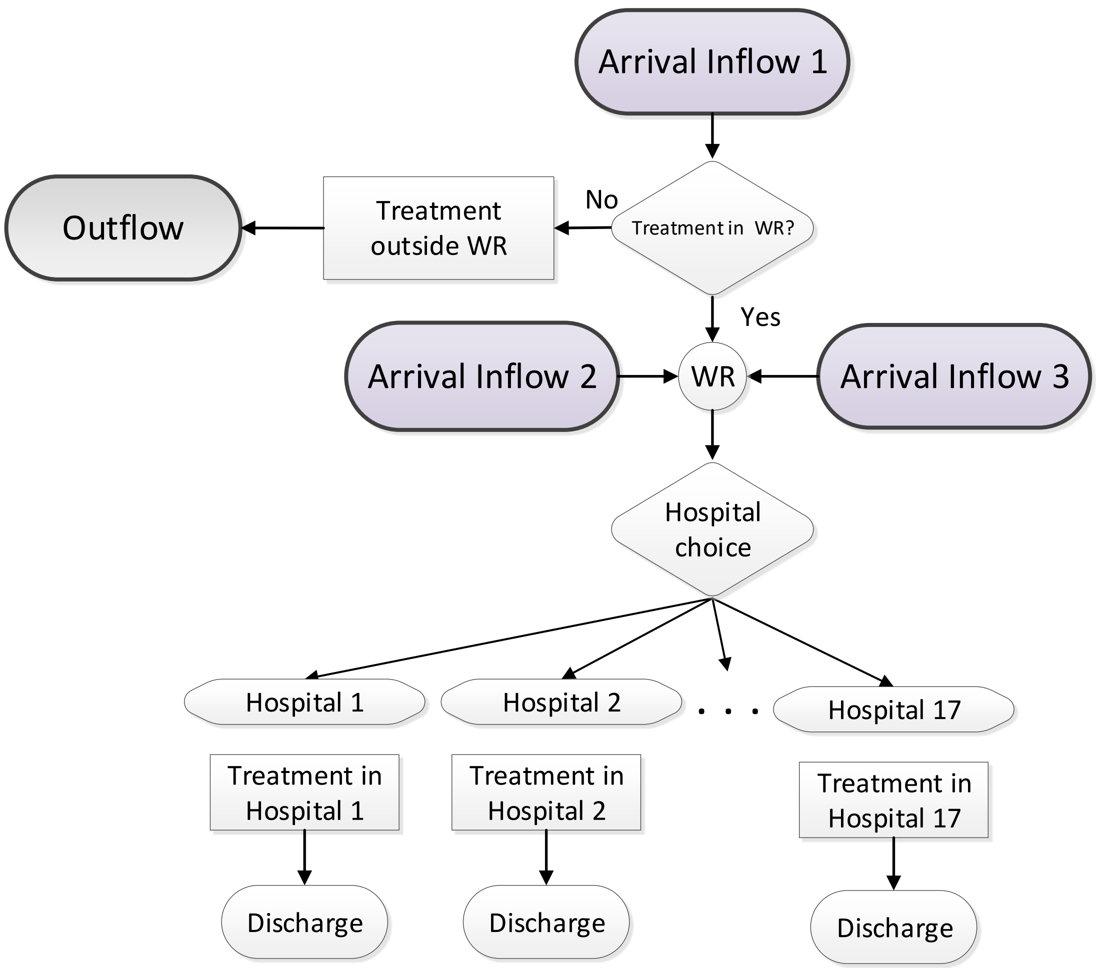

Figure 4: Flowchart of the discrete event simulation model.

The main input flow generates, on an hourly basis, the number of patients belonging to every age-gender cohort of the WR population. There are 36 mini flows describing arriving patients separately for 36 age-gender cohorts. Analysis of historical data suggests that there is a strong variability related to the calendar month; therefore, the non-stationary Poisson process was used to represent time-varying arrival rates, separately for 36 mini-flows. We use 432 (36 cohorts * 12 calendar months) λ parameters, where λ represents the average number of arriving patients during a fixed time interval (per hour). On arrival, a patient acquires a number of attributes, including age, gender, place of residence, servicing hospital, number of services, and the patient category. The attributes are interrelated and mutually dependent. For example, *Patient's Category* depends on the hospital selected by a patient and the number of services received by the admitted patient. The latter depends on the patient's age and gender.

3.5 Hybrid Simulation

Using 2010 NHF data (see par. 3.2), similar to (Strunk et al. 2006), we calculated age-specific demand rates for each age-gender cohort. We received 36 values (Figure 5) describing the varying effect of aging on inpatient hospital demand. It is clear that older age-gender cohorts are likely to generate higher demand for hospital services.

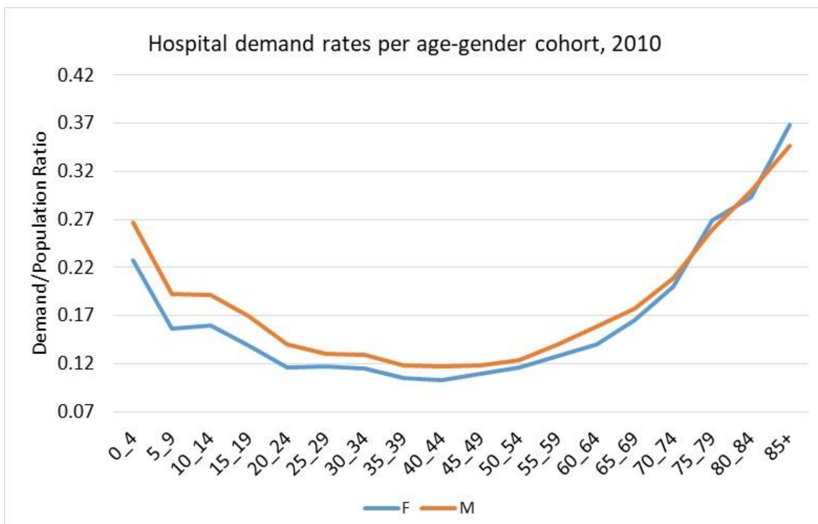

Figure 5: Hospital demand rates for each age-gender cohort [patients/population].

The output of the SD simulation model forecasts the demographic changes of the WR population over the next 32 years (up to 2050). These values, describing the quantitative status of each cohort as predicted for each simulated year, are saved in external files. We multiplied the calculated age-specific demand rates for people of each age-gender cohort by the total number of people of that age and gender in a given year as reflected in the projections forecasted by the SD model. We received the projected values of the demand for hospital services for the WR population for every cohort during the simulated time horizon

The projected demand is used to calculate 432 new values of λ parameters to be included in the non-stationary Poisson process to represent time-varying arrival rates of patients arriving at WR hospitals each year during the 15-year simulated horizon (to the year 2030). Discrete simulation begins from an empty and idle state and lasts 365 days (1 year) with arrival rates calculated from population estimates delivered by the SD model and utilization rates extracted from historical data. The DES simulation is repeated for each year of the time horizon (15 years), holding the utilization rates per cohort as well as all other drivers of hospital demand constant. It is clear that besides demography, other important factors influence healthcare expenditures, especially medical and technological progress, political decisions, and economic conditions. However, these factors are not included in our model.

4 RESULTS

4.1 Population Estimates

The forecasted trends for basic demographic parameters (see Table 1) enable the formulation of several dozens of scenarios describing the alternative possibilities for the evolution of Polish population. Among these scenarios, four were officially accepted by the Government Population Council. We have adapted the assumptions of these four officially accepted scenarios for the WR population, and designed experiments to test the effect of aging on hospital demand (see Table 2).

Scenario 2 is the most probable scenario, and Scenarios 1 and 3 are considered as alternatives. The fulfillment of Scenario 4 depends on the success of the governmental family-oriented program. All scenarios, after an initial period of population growth, predict a stable, decreasing trend in the WR population, (Figure 6). The intensity of the initial growth and later reduction differs for each scenario.

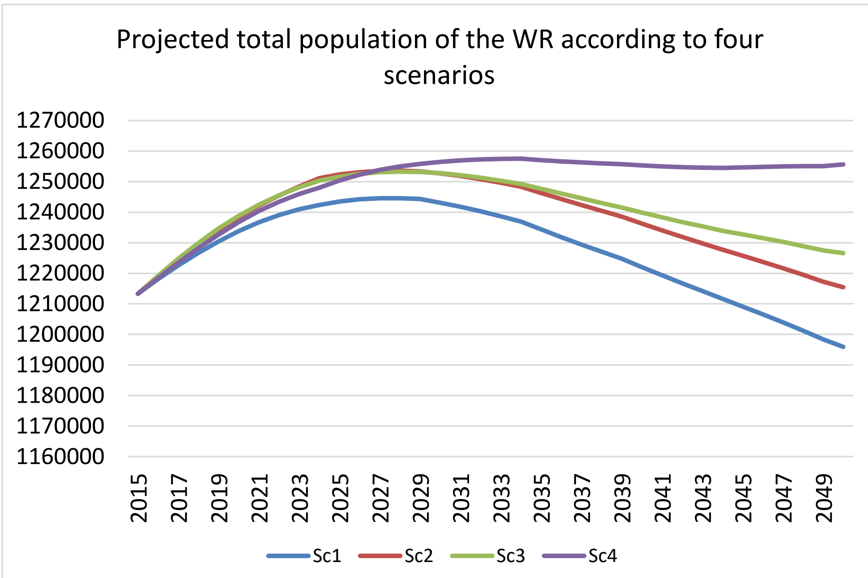

Figure 6: Output of the SD submodel.

All scenarios predict the comparable structure of population in future age groups. This is due to the fact that for the scenarios with low fertility rates, low mortality rates and high life expectancy are assumed (Table 3).

Table 3: Structure of population according to age groups in 2016, 2020, 2030, and 2050. All data in [%].

Age group	2016 historical	2020				2030				2050			
		Sc1	Sc2	Sc3	Sc4	Sc1	Sc2	Sc3	Sc4	Sc1	Sc2	Sc3	Sc4
0_4	5.26	4.89	4.93	4.96	5.11	4.16	4.22	4.26	4.61	4.39	4.62	4.91	5.28
5_59	70.61	70.42	70.32	70.30	70.28	70.38	70.68	70.65	70.97	64.14	64.00	64.00	64.54
60+	24.21	24.69	24.86	24.86	24.69	25.46	25.83	25.83	25.45	31.47	31.37	31.09	30.18

4.2 Hospital Demand

We used two measures to explore the effect of population aging on hospital demand: the arrivals to the WR hospitals according to three complex age groups (0–4, 5–59, and 60+) and the number of patients classified in each of the five cost categories (see par. 3.2). The simulations indicate that from 2016 to 2030, the predicted growth of the WR population will result in constant growth of the WR hospital demand (Figure 7) from 4% to 6%, as compared to the year 2016, in all the four tested scenarios.

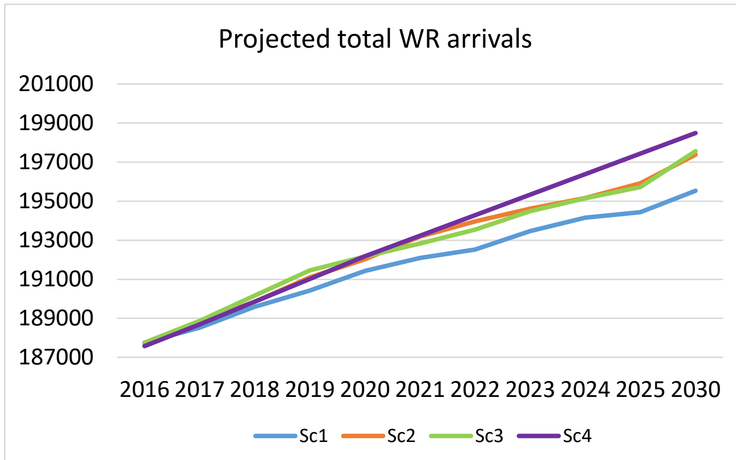

Figure 7: Output of the DES submodel. Projected trends of the WR arrivals according to four scenarios.

Although the growth rate in overall WR admissions between 2016 and 2030 is predicted to be higher by at most 6% (Figure 7), population aging will increase the number of arrivals in the oldest age group by as much as 16.5% in Scenario 1, 18.4% in Scenario 2, 18.8% in Scenario 3, and 17.0% in Scenario 4 (compare: high positive values in Figure 8).

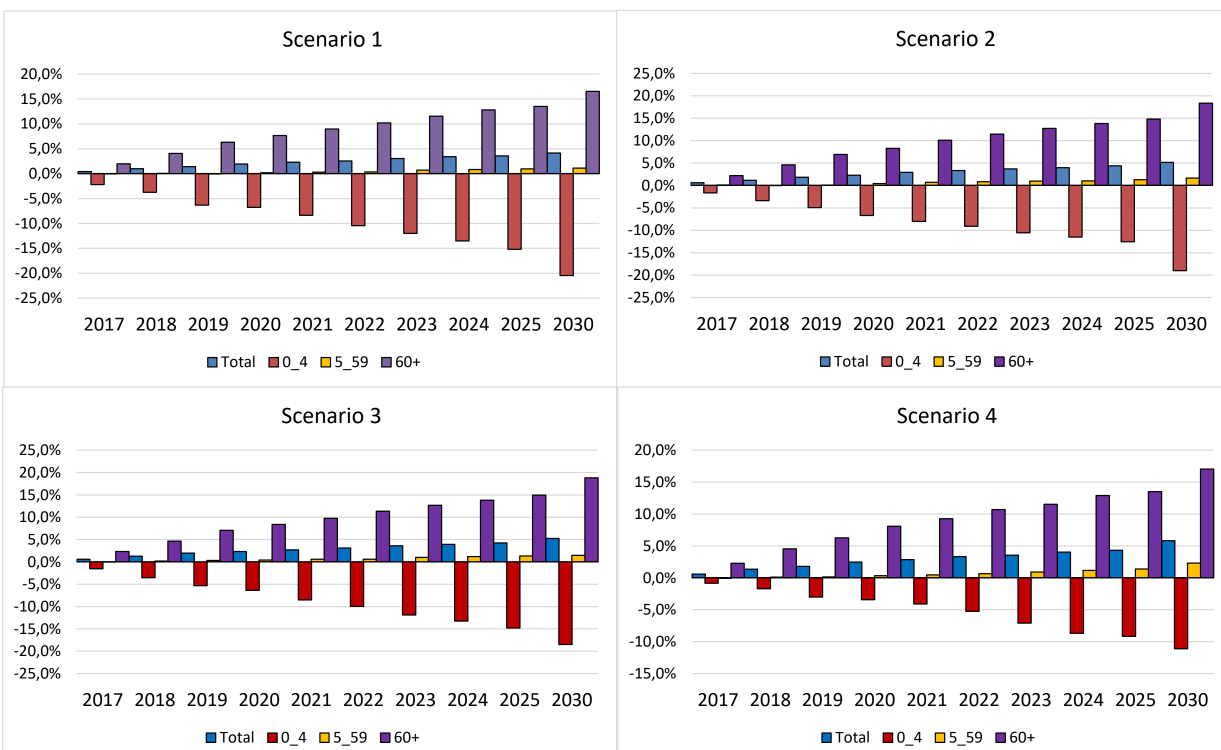

Figure 8. Projected annual percentage changes of the WR arrivals in three age groups relative to 2016.

This would translate to over 70 000 oldest patients in 2030 from the current level of 60 000 in 2016, which gives an extremely high value of increment. During the same period, the number of arrivals for the youngest cohorts will significantly decrease (compare: high negative values in Figure 8).

We explored the impact of the predicted intensification in the number of arrivals of elderly people on the budget needed to cover the increased demand. For further analysis, we chose the most probable scenario according to governmental forecasts, Scenario 2. This scenario perceives that the aging trend during the next 15 years will influence the cost categories unevenly. As the total demand for hospital services increases, the number of patients in every cost category increases as well; however, the rates of growth are strongly differentiated (see Figure 9). Although the total demand between 2016 and 2030 will increase by 5.2%, the number of patients classified into Category 1 will be greater by 3.48%, Category 2 by 4.31%, Category 3 by 4.99%, Category 4 by 7.36%, and Category 5 by 1.8%. It is very likely that the increasing rate in Category 4 patients results from population aging.

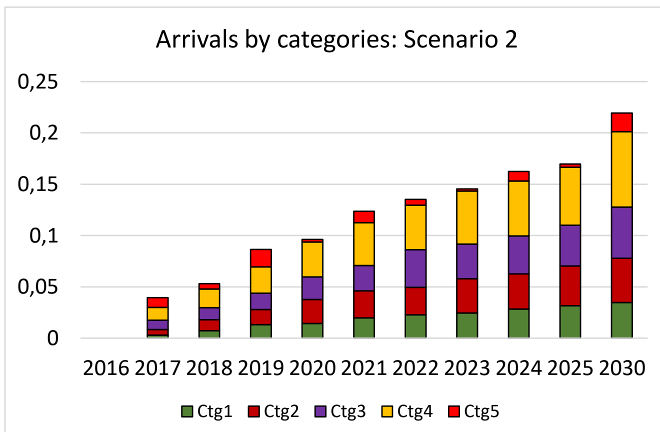

Figure 9: Output of the DES submodel. Projected annual percentage changes of the WR patients classified into five cost categories relative to 2016. Scenario 2.

5 DISCUSSION AND IMPLICATIONS

This study seeks to extend the previous research on the effect of population aging on the demand for hospital services (Mielczarek and Zabawa 2016; Mielczarek and Zabawa 2018). We have contributed to the field of hybrid simulation by combining both system dynamics and discrete event simulations. Doing so enabled us to achieve a holistic, long-term insight into the demographic tendencies in WR and a more detailed analysis of the process of delivery of inpatient services. The important advantage of such an approach is the ability to simultaneously perform a deterministic simulation driven by complex, internal feedback loops and a stochastic simulation that follows uncertain trends describing the arrival processes. We are convinced that the complementary use of two simulation models adds new value to the process of predicting the future needs by considering a range of factors that describe both the population and the region.

Our analysis provides useful guidance for healthcare services planning at the regional level. The effect of WR population growth on total healthcare demand will be small but significant; however, it will have a larger impact on the number of elderly patients and the delivery of certain types of more expensive services provided in WR hospitals. Our analysis does not include the influence of technology changes on healthcare demand, and we believe that the growth of expensive services delivered to inpatients will be much more significant. The regional healthcare authorities must plan for adequate capacity for these types of services performed in WR hospitals in the near future.

Our combined SD-DES model has some limitations. We have assumed that age-specific demand rates for each age-gender cohort are constant throughout, although one might wonder if changes in demographic structure and other tendencies such as advancement in technology affect different age-gender groups disproportionately. Therefore, we plan to include the future fluctuations of the rates of inpatient care as input parameters for simulation experiments. Next, there is a clear feedback loop between demographic trends and the epidemiological parameters. For example, the changes in population structure affect the risk factors for a range of medical conditions. The changing risk factors modify the morbidity trends and thus influence the prevalence of diseases. Lastly, geographic accessibility of healthcare facility is a strong determinant for older patients and demand may vary accordingly to the supply of hospital services.

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