Modelling Population Growth, Shrinkage and Aging using a Hybrid Simulation Approach: Application to Healthcare

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Abstract: This paper describes a hybrid simulation model that integrates the System Dynamic approach with discrete time control to formulate the projections of population evolution. The study relies on historical demographic data and the officially formulated scenarios for the most likely population projections developed for the region. The results of the simulation experiments provide valuable insights into dynamics of regional demographic trends and offer a well-defined starting point for future research in the health policy field. The intensity and structure of the demand for healthcare services depend heavily on age-gender profiles that change due to ongoing extensions of the average expected length of life, the aging of population, the continuing trend of declining number of births and the steadily growing number of deaths. The preliminary findings show promise in using the hybrid simulation approach for more advanced exploration of demography dependent health policy issues.

1 INTRODUCTION

Credible demographic forecasts are an essential and imperative input for a range of economic studies. The precise replication of population structure affects the proper examination of long-term implications of population dynamics on macroeconomic performances. Quantitative evaluations that include the effects of population changes must consider demographic forecasts. There is, for example, considerable interest in the impact of population aging on economic growth and the macro-economy in general (Lisenkova *et al.* 2013). Financial sustainability of social security systems depends on the size of the older population and the percentage of insured employees (Tian & Zhao 2016). Population dynamics affect urban development and land use (Lauf *et al.* 2016). Population projections are utilized as inputs in health policy models (Ansah *et al.* 2014).

One approach to including the population forecast in the scientific analysis assumes that the population projections are derived from census data and are based on moderate demographic scenarios developed and published by national statistical units or world-wide organizations such as the World Bank or the United Nations. Another approach is to utilize the stochastic forecasting method to predict population evolution. Time series modelling techniques are frequently adopted to estimate the basic input parameters such as fertility, mortality and migration rates (Lutz *et al.* 2001). This well-developed methodology allows for short-term fluctuations in vital statistics. The original method of stochastic forecasting with revisions of demographic forecasts was developed by Lassila *et al.* (2014). The primary concept of their approach is that each update in the official population projection alters people's perception of the future.

Simulation studies are vital tools for analysing the behaviour of many real-life systems and age structured population models are often part of these studies. When population projections are formulated within simulation models, two options are available. The stochastic population sub-models take into account demographic uncertainty. Primary parameters such as fertility, mortality and migration may be considered as stochastic processes. Samples are taken from the predictive distributions of future population, and utilizing the Monte Carlo (MC) stochastic simulations, the population distribution is obtained (Tian & Zhao 2016). Certain authors (Davis *et al.* 2010) prefer to use micro-simulation to

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model individual behaviour and the MC process to convert probabilities into characteristics of individuals.

Another well-known simulation methodology utilized to capture the population evolution is System Dynamics (SD); this methodology proved to be useful in policy formulation and addressing dynamic complexity of the system (Homer & Hirsch 2006). For example, Barber and Lopez-Valcarcel (2010) used a SD submodel to simulate a demographic pyramid to analyse the demand for medical specialties. Masnick and McDonnel (2010) modelled the population utilizing the SD approach to link individuals with health conditions to the clinical workload.

These two approaches differ significantly. MC simulation is performed on one or more typical individuals who are used to describe the experience of a larger group within a population. A model simulates hundreds or thousands of potential scenarios and produces forecasts as outputs, usually in the form of relevant means, probabilities and a dispersion of results similar to an expected value. The SD approach is particularly helpful when attempting to formalize a mental model of a given problem. In addition, it is useful when analysing the relationship between a system's structure and its behaviour after changes have occurred. Typically, SD models are not designed to yield exact numerical predictions but are intended to explore multiple policy options.

The overall goal of our project is to build a hybrid simulation model that would allow alignment of short-term demographic forecasts with health policy models to predict the future demand for healthcare services. In this paper, we present the SD population submodel driven by the separate discrete module that controls the frequency of near continuous computation and shifts the members of age cohorts. The hybrid model enables us to perform time-step simulations that describe population evolution according to the continuous SD paradigm. The ongoing demographic changes directly influence the discrete event simulation (DES) submodel that generates the discrete demand for healthcare services.

The values of the input parameters are calculated based on forecasted rates of the primary demographic parameters, retrieved from projections published by the Polish Central Statistical Office (CSO). The output is expressed by the total population in every cohort; however, each individual in our model is distinguishable. In the latter phase of the simulation, when individuals with health conditions first arrive at the healthcare system, the model records their movements. In addition, the model creates and adjusts attributes that describe individual patients. These attributes are sampled from empirical distributions and characterize every individual patient.

In our research, we expect to verify the credibility of the approach based on the System Dynamic method developed by Forrester (1968) and allow a modification of the time step *dt* inside the population module in response to feedback from the discrete module.

2 HEALTHCARE SIMULATION

Simulation plays a vital role in healthcare decision making (Mustafee *et al*. 2010). It is widely utilized in research studies and is also a popular educational tool and decision support technique that allows stakeholders to assist in long-term planning processes. Simulation modelling provides an opportunity to gain deeper understanding of mass events such as the spread of infectious diseases (Hughes *et al.* 2006, Alfonesca *et al.* 2000); to analyse the performance of a particular healthcare unit: hospital, operating theatre, outpatient department and diagnostic centre (Testi *et al.* 2007); or to forecast the future behaviour of a particular system under study (Ashton *et al.* 2005).

Numerous applications of simulation have been conducted in healthcare in past decades and according to many surveys, the discrete-event simulation approach (DES) is the most often used technique in the field of healthcare management (Jun *et al.* 1999, Mielczarek & Uziałko-Mydlikowska 2012). However, in the health policy field, when the objective of the study is to establish long-term predictions of the total level of demand for health services, the SD approach is also frequently used. Health policy studies usually begin with an analysis of the population structure and its dynamics on a local, regional or national level. The intensity and structure of population needs depend on age-gender profiles that, in turn, evolve according to changes that occur regarding average expected length of life, levels of birth and death rates and fluctuations in migration parameters (Ansah *et al.* 2014). Additionally, the need of services by patients with diagnosed diseases change in relation to the amount of time that has passed from the moment a diagnosis was formulated (Caro *et al.* 2006).

According to (Lane *et al.* 2000), when using the system dynamic approach, we lose the ability to include uncertain factors that are prominent in healthcare systems. In addition, patient-oriented issues are considered on the aggregate, instead of individual level. However, what we gain is a systematic view of patient movements and a more strategic perspective of system behaviour.

In this paper we used the well-established methodology of SD modelling to capture overall population evolution. We modified the approach to allow for the use of age-gender cohorts simulated by the SD submodel to generate discrete demand for healthcare services.

3 POPULATION

The population of interest resides in the two subregions of Lower Silesia, the fourth largest region in Poland. These two subregions are denoted as the Wrocław Region (WR) and encompass nine administrative districts: the capital of Lower Silesia (Wrocław) and eight districts that are nearby the capital. According to the Central Statistical Office (GUS, 2015) the total WR population increases annually (Table 1, Figure 1) for both genders.

Table 1: Structure of the WR population according to age-gender groups from 1995 to 2014.

	1995	2000	2005	2010	2014
Total number of women (F) and men (M):					
F:	604848	604226	608160	622112	633074
M	561852	557928	558057	570442	579707
Children ages 0–4 as % of total number of women:					
F:	5.05%	4.19%	3.87%	5.03%	4.82%
M:	5.72%	4.79%	4.45%	5.74%	5.62%
People ages 60+ as % of total number of women/men:					
F:	19.16%	20.40%	20.79%	23.38%	26.17%
M:	13.57%	14.05%	14.19%	16.84%	19.52%

4 MODEL

Our approach to chronological ageing is based on the concept described by Eberlein *et al.* (2011). The outline of the first, basic version of the model was presented in (Mielczarek *et al.* 2014). To better visualize the general concept, we present population aging chains using System Dynamics notation (Figure 2).

Ten state variables define the population inside ten cohorts: five female and five male cohorts. Each cohort represents a separate state variable described by the stock level. In accordance with Krahl (2009), we defined the internally generated state-change events and linked them with state variables. The state variables change at discrete times when their associated flow rates also change. Input and output flows that move to and from the particular stock are aggregated into one dynamic object that controls the appropriate state variable. The resultant flow instantly increases or decreases the number of individuals in the cohort. This eliminates rounding errors and improves accuracy of the simulation.

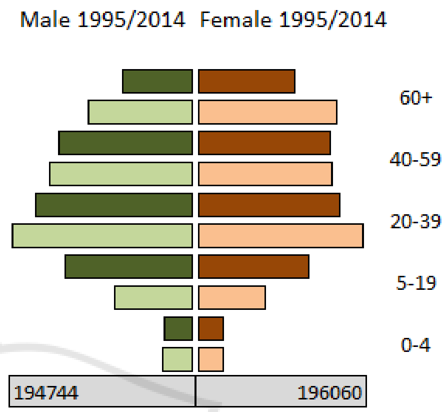

Figure 1: Comparison of age pyramids of the WR population using historical data from 1995 (dark colour) and 2014 (light colour).

The initial population data matches historical conditions in 2002 based on information published by the CSO (GUS, 2015). The simulation begins in 2002 and runs through 2014 according to parameters calculated on the basis of historical values extracted from statistical data bases for the Wrocław Region. Beyond 2014, the exogenous parameters are extrapolated based on the forecasts published by the CSO (Waligórska *et al.* 2014).

4.1 Computer Model

The computer model was constructed in the ExtendSim environment. There are two submodels that closely cooperate with each other: DES sub-model was developed using modules from the *Item* library and SD submodel was based on the *Value* library. Both libraries are available in the standard software package. The model uses over 700 elementary blocks and a number of integrated blocks defined according to the hierarchic approach.

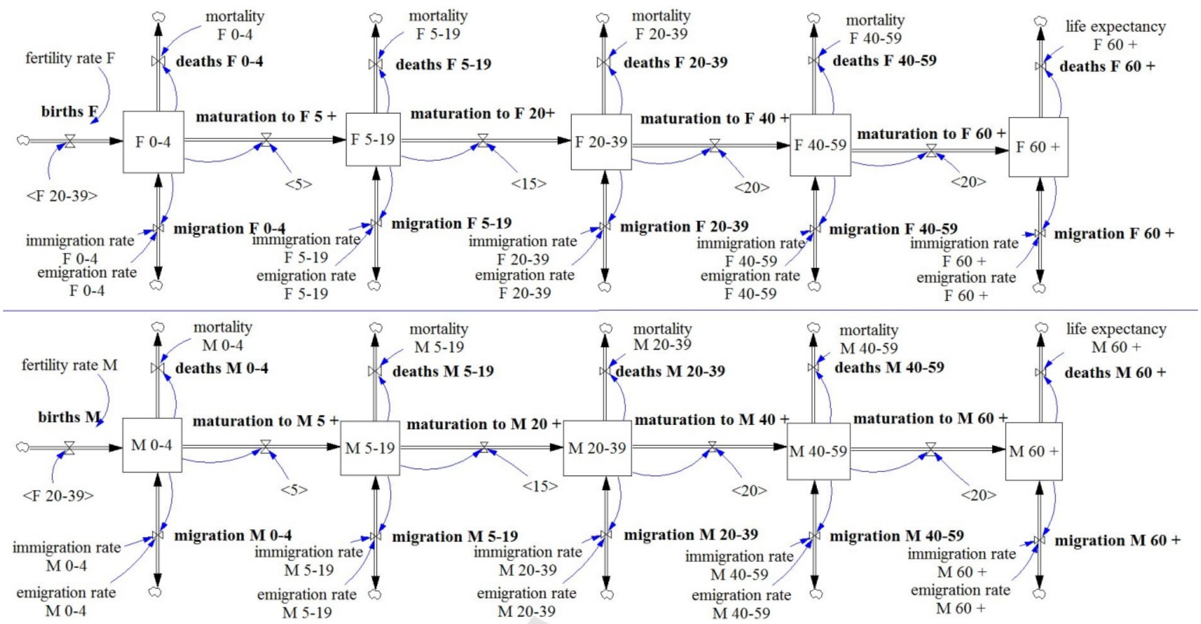

Figure 2: Population aging chains.

The SD submodel simulates the on-going evolution of the population. It is based on ten main integrated blocks representing ten age-gender population cohorts (see Figure 2). The crucial role inside the hierarchic SD blocks is played by the *Holding Tanks* – the elementary blocks that represent the *stocks* of the System Dynamic approach.

The DES submodel generates patients arrivals to the healthcare system. It consists of the integrated block that simulates the prevalence of needs-for service events. The additional DES module helps to control the passage of time inside both of the submodels. Consequently, the control of the SD objects is overtaken by the discrete blocks.

The built-in mechanism for data base management is applied to enable storing all the input parameters and output simulation data in the external data bases.

4.2 Cohorts 0 to 4

The cohorts F 0–4 and M 0–4 (Figure 2) describe the youngest children, separately for females and males. The youngest cohorts are affected by two input and three output flows. There is one primary and one additional input flow: *births* and *immigration* and there is one primary and two additional output flows: *maturation*, *deaths* and *emigration*.

The primary input flow (*births*) for both females and males depends on the current number of female 20–39 cohorts. Historical values of fertility rates (from 2002 to 2014) are estimated based on published data (GUS, 2015). Female fertility rates are calculated by dividing the total number of girls ages 0–4 by the total number of women ages 20–39 for each historical year. Accordingly, male fertility rates are calculated by dividing the total number of boys ages 0–4 by the total number of women ages 20–39.

The *migration* input and output flows depend on migration rates (immigration and emigration) that are calculated based on data describing the number of young children moving to and from the Wrocław Region and the total number in the youngest cohort.

The *deaths* output flow is driven by death rates calculated based on the number of deaths among the youngest WR citizens and the total number of children ages 0–4 living in the Wrocław Region, separately for females and males.

The primary output flow (*maturation*) is interpreted as the average residence time that is necessary for an individual to leave the younger cohort and enter the older one. The values of maturation time differ between every set of cohorts. It is, for example, five years between F 0–4 and F 5–10 but 20 years between M 40–59 and M 60+.

Beginning in 2015, the hypothetical values of female and male fertility rates, migration rates and death rates are adopted according to different scenarios of population projections *(Waligórska et al.* 2014)

4.3 Cohorts 5–19, 20–39 and 40–59

The series of cohorts 5–19, 20–39 and 40–59 represents the population that is between four and 60 years old, separately for females and males. Stocks include three input and two output flows defined similarly to those of the youngest cohort. The only difference relates to primary input flow, where instead of *births*, we use *maturation from* the previous cohort.

4.4 Cohort 60 +

The final two cohorts, F 60+ and M 60+, describe the oldest population, separately for females and males. The cohorts are affected by two input and two output flows: *maturation* from the previous cohort, *immigration, emigration* and *deaths.* The primary output flows (deaths) are defined using the average life expectancy for female/male(s) at the age of 60. Historical values of these parameters (from 2002 to 2014) are estimated based on data published by the GUS (2015). Beginning in 2015, hypothetical values of female and male average life expectancy are adopted according to different scenarios of population projections (Waligórska *et al*. 2014).

4.5 SD-DES Time Mechanism

The SD modelling approach is based on differential equations and therefore enables the simulation of a continuously changing system as well as the continuous observation of the dynamic behaviour of that system over time. In demography studies, however, a more appropriate technique is to push elements from one cohort to another at discrete intervals to capture key events such as births and deaths.

The time-step mechanism implemented in our model is designed with the assumption that time passes according to constant discrete values. At discrete moments, the flow rates change and all input and output flows that move to and from a particular stock are aggregated into one dynamic object. The resultant flow instantly increases or decreases the number of individuals in the cohort and the new values of stocks are registered. This procedure is similar to sampling the values of stock levels from the population model and then downloading the obtained values into separate objects (so called *holding tanks*). An important feature of this approach is that not only is the number of people belonging to a particular cohort at any moment of simulation registered, but individual attributes are maintained (for example age, sex or other attributes if they were assigned to the moving objects). This ability to *memorize the attributes* is an extremely valuable quality when attempting to link the SD and DES approaches.

The values sampled from the *holding tanks* are then used to parameterize the inter-arrival time distributions that describe the patient's presentations to the healthcare system and create the demand for healthcare services. The discrete objects and their attributes may enter the DES model without any delay.

4.6 Model Testing and Calibration

The output measures of the population sub-model are the number of individuals in every cohort as registered during the simulation at the end of the calendar year. The simulation begins in 2002 and runs through 2014; it runs using parameters estimated from historical values. Therefore, the population module was tested for fit against 2002–2014. Figure 3 presents two age pyramids for 2014: the dark-coloured pyramid represents the distribution of the WR population based on historical data published by the GUS (2015). The light-coloured pyramid represents the simulation data.

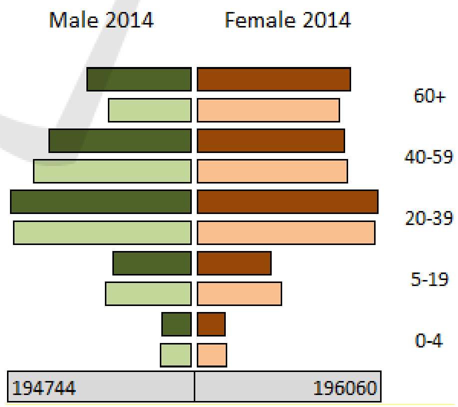

Figure 3: Comparison of the age pyramids of the WR population built from historical (dark colour) and simulation (light colour) data.

Relevant parameters of the model include the values of time that are necessary for the individual to transfer from one cohort to another. The proper values of *maturation lengths* are determined utilizing an optimization technique delivered by

ExtendSim Optimizer. This model is run several times, and the primary function is to minimize the total differences between the number of males and females in particular cohorts. This infers that although, in consecutive years, there are differences between historical and simulation data when comparing the particular age cohorts, the difference that relates to the total number of population is minimized. The *maturation lengths*, which are found when the optimization process is not able to provide more optimal solutions, are used during the simulation experiments in forecasting the future WR population.

Mean absolute percentage errors (MAPEs), calculated for the entire WR population in the particular years, indicate that the simulation model provides on average acceptable results for the estimation of the WR population (Table 2).

For particular age cohorts in 2014, the MAPEs range from 5.72% to 10.93% (male population) and from 4.87% to 9.88% (female population). These results demonstrate the usefulness of the System Dynamic approach to capture the population evolution.

Table 2: Mean Absolute Percentage Errors (MAPEs) calculated between historical and simulation data for the total number of the WR population in particular years.

Year	Male	Female
2002	0.04%	0.13%
2003	0.17%	0.20%
2004	0.27%	0.31%
2005	0.54%	0.42%
2006	0.72%	0.49%
2007	1.03%	0.58%
2008	1.22%	0.71%
2009	1.28%	0.75%
2010	0.24%	0.20%
2011	0.29%	0.19%
2012	0.24%	0.39%
2013	0.06%	0.56%
2014	0.05%	0.48%

5 SIMULATION EXPERIMENTS

From among several dozens of scenarios of projection assumptions for population dynamics discussed by the Government Population Council in 2014 (Waligórska *et al.* 2014), four scenarios were considered to be the most likely, but only one scenario was officially recognized and published by the CSO. Below, we present the simulation results assuming that the development of the WR population will be affected by demographic trends described in the official forecasts published by the CSO for the years 2014–2050.

5.1 Simulation Scenario

The following assumptions were included in the model to run the simulation beyond the year 2015:

- Fertility rates. It is assumed that fertility rates will incur a slight decline during the next few years and then a gradual increase will be observed. In 2035 the increase of fertility rates values is expected to be approximately 20.0% (males) and 22.0% (females).
- Death rates. It is expected that death rates will increase gradually from 2015 to 2035. However, the number of deaths in the middle-aged cohorts (M 40–59 and F 40–59) will slightly decline.
- Life expectancy. The difference between Poland and European countries will remain at the same level during the next 20 years. This indicates that in the year 2035, a woman age 60 will live on average 27.75 years and a man at this same age will live on average 24.27 more years.
- An alignment trend will be observed between emigration and immigration and in the year 2035, the international and internal net migrations will decrease to almost zero. The total number of immigrating and emigrating individuals will decrease by approximately 20%.

5.2 Simulation Results and Discussion

The forecasted number of male and female populations within 10 distinguished age cohorts were obtained, see Figure 4. The simulation results are compatible with the CSO forecasts. Aging of the population is an irreversible phenomenon. The *old-age rate*, i.e., the number of the oldest cohorts among the entire population will increase from 18.84% in 2014 to 22.17% in 2035. The *median age of population,* i.e., the age that half of the population have not yet reached and the other half has already lived, will in 2035 be approximately 50 years. The subpopulation of females will exceed the male subpopulation by more than 10%. The decrease of children 0–18 years old in 2035 compared to 2014 will be negligible.

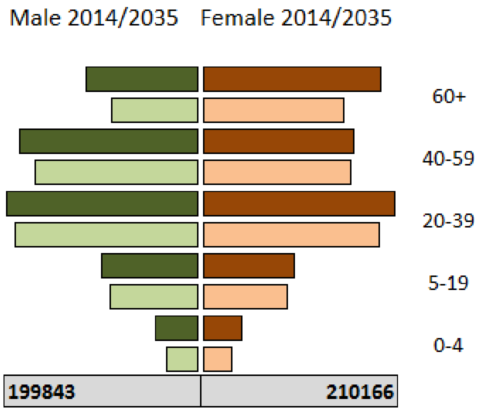

Figure 4: Comparison of the age pyramids of the WR population built from the 2014 historical (light colour) and 2035 simulation (dark colour) data.

Figures 5 and 6 present selected output generated by the SD module and directed to the DES module. The stock level that represents the total number of the F 60+ population (the upper line) from 2014 to 2016 is converted to the flow of patients arriving to the healthcare system (the bottom line). The indistinguishable mingling of individuals, often referred to as *the blending problem*, was modelled by the discrete volume of needs-for-service expressed by women ages 60 and over, inhabiting the WR. The results of the simulation demonstrate the integration of two opposite perspectives: the projection of long-term population evolution based on the aggregated data (the upper line) and discrete movement of individuals arriving to healthcare system (the bottom line). The added value of this approach is the flexibility in the modelling of the arrival process. Figures 5 and 6 present the number of patients F 60+ arriving to health units; however, the graph 5 was created based on daily sampling and graph 6 – based on weekly sampling.

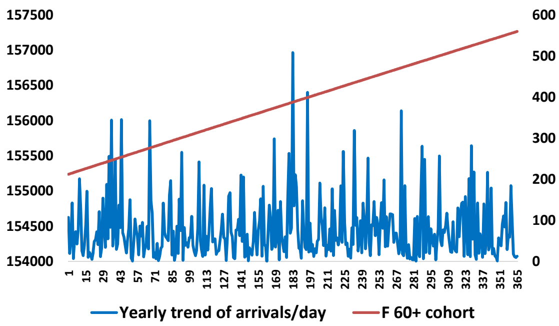

Figure 5: Daily weekly trend of arrivals/day sampled from F 60+ cohort.

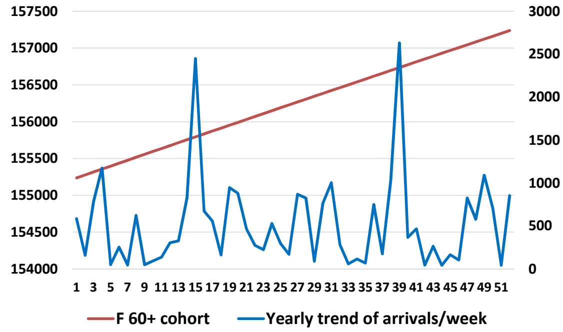

Figure 6: Weekly trend of arrivals/day sampled from F 60+ cohort.

6 CONCLUSIONS

Changes in population demography have a significant effect on healthcare demand. The provision of healthcare resources is a long-term planning task and the increasingly complex nature of problems faced by healthcare managers stimulates growing interest in hybrid simulation approaches.

We have 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. System Dynamics is a well-known and often applied simulation technique to model demography changes. This time-step simulation produces, however, the indistinguishable blending of age/gender cohorts. The discrete event simulation is, in turn, the most often used technique in the healthcare management field. This approach easily captures individual choices made by patients. Individual attributes, such as age, place of residence, type of injury and requested services, influence patients' decisions and consequently determines the utilization of healthcare resources. Our goal was to construct the hybrid simulation model that would allow linkage of short-term demographic forecasts with a discrete model to predict future demand for healthcare services.

This analysis is a first step in the direction of more comprehensive studies and several research topics seem to be warranted. The aging chain population model needs more extensive refinement and testing. Although the total population is precisely simulated in the model, the sizes of particular cohorts require additional calibration. We also seek to better specify the uncertainty describing the morbidity trends and to determine the impact of this uncertainty on the demand for healthcare services. It could be also interesting to parameterise the model with some external/indirect incentives such as the economic growth, the development of education or transportation infrastructure, and the influence of the national pro-demography programme that has been recently started by the Polish Government. The so called *family 500+* programme supports the families having at least two children by granting the monetary educational benefits. The programme is intended to increase the fertility rates.

There are still numerous technical problems that need to be solved to better integrate two modules driven by different simulation paradigms. For example, the single simulation run lasts about 25 minutes. This length of time is unacceptable when running the stochastic simulation that requires a number of independent replications.

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