A System Dynamics Model to Study the Impact of an Age Pyramid on Emergency Demand

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Abstract: This paper describes a system dynamics simulation model to analyse the relationship between age pyramid and the volume of patients arriving to hospital emergency departments located in a sub-region of Lower Silesia of Poland. The study relies on demographic and historical demand data, and the cohort forecasts for the population of the region. The results of the simulation experiments provide insights into the relationship between sub-regional demographic trends and population needs in relation to hospital emergency arrivals. The preliminary findings indicate that the forecasted long-term demographic changes in the population may increase the number of emergency patients in the area.

1 INTRODUCTION

This paper follows on our previous study and reports on the use of simulation methods to support healthcare policy planning on a regional level. The results of the first stage of the research were described in (Mielczarek 2013; Mielczarek 2014). The overall goal of the study is to assess the volume of emergency services (ER) to be contracted by the regional branch of National Health Fund (NFZ) in admission units (AU) and emergency wards (EW) located in Lower Silesia region in Poland to cover the demand for emergency medical treatment. In our previous study, a discrete event simulation model (DES) was built to plan the number and value of hospital emergency services to be contracted by NFZ with providers, for the following year, to meet the needs of the population and to ensure that the cost of the services to be delivered in emergency units is reimbursed by the contract. This study is an attempt to identify the relationship between the number of emergency hospital visits, as forecasted based on the number of patients arriving at the hospital emergency departments in the area, and the demographic parameters of the population.

The challenge when supporting the decisions related to capacity planning at the regional and national level is the demand estimation. In practice, *demand* for healthcare services is defined based on the *supply*, i.e. the number of services delivered to patients, because only this type of information is available in the source databases. When dealing with elective services, the separate measures of supply (outpatients seen and inpatients admissions) and referrals (outpatient referrals and decisions to admit) are available (Martin *et al.* 2007). This approach, however, may not be used in relation to the majority of healthcare services. For example, the emergency care is provided without limits for every patient who requires medical assistance and it is not possible to separately estimate demand and supply.

In our research proposal we assume that the estimated demand for emergency services is driven not only by the historically registered population needs described by the services that have already been delivered to patients, but also by the factors directly related to the population structure. The relationships between changing ER needs of the population under study and the demographic parameters (namely: age-gender groups and migration rates) will be simulated using system dynamics approach. Based on historical data and external forecasts of demographic trends published by Central Statistical Office (GUS, 2014), we wanted to examine the influence of the fluctuations in the age pyramid on the volume of ER needs expressed by the patients arriving at hospital AU/EWs in the area.

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2 THE METHOD

There are four main simulation approaches commonly used to study healthcare management problems: Monte Carlo (MC), discrete event (DES), agent based (ABS) and system dynamics (SD). All these methods have their strengths and limitations, and the choice of a particular technique depends mainly on the area the model is going to be applied. According to Lagergren (1998) and Mielczarek & Uziałko-Mydlikowska (2012) five main areas of simulation models applied in health services may be distinguished:

Health policy: when making decisions that relate to national, regional or local health planning strategies;

Improvements: when focusing on the current work of service providers in order to identify bottlenecks and suggest improvements of system performance;

Forecasting: when trying to predict future demand and define the resources that will be necessary to cover the forecasted population needs;

Medical decisions: when conducting the assessment of various operational decisions in medical practice;

Extreme events: when determining the preparedness and efficiency of healthcare system in cases of unexpected events and threats.

DES is by far the most frequently used modelling technique in *improvements* (Bowers & Mould 2004), *forecasting* (Harper, Phillips & Gallagher 2005) and *extreme events* application areas (Whitworth 2006). This dominant position of DES models is particularly justified when studying system performance, testing different alternatives of system operation, and suggesting system improvements. MC method is applied across all of the areas, usually as a supportive technique, and it is a preferred modelling approach for analysing *health policy* and *medical decision* issues (Jacobson, Sewell & Weniger 2001). SD is selected mainly to tackle problems in epidemiology and disease prevention within *health policy* and *forecasting* areas (Homer *et al.* 2004; Kasaie *et al.* 2010). ABS is still not very popular among healthcare researchers and very few examples of agent models can be found in literature (Cabrera *et al.* 2011).

We chose the SD method for the development of our projections because this approach enables to include not only quantitative but also qualitative aspects of the system. The qualitative parameters are introduced by the use of casual loops that link together the risk factors and the decision input variables. Moreover, system dynamics modelling is based on the aggregated attributes and therefore it enables more strategic perspective of the management of the system. The demography related factors like aging of the population, deaths, migrations, and the continuous progress of certain diseases create a constantly changing situation influencing the number of patient presentations to AW/EUs. There are however long delays between causes and effects that hinder the process of modelling especially when trying to determine long-term population dynamics and explore implications for the health capacity planning strategy. The unique concept of *time spread delays* introduced through stock-and-flow structures in SD simulation models is ideal for this purpose.

3 LITERATURE REVIEW

There have been many applications of SD in healthcare, especially in the last decade (Mustafee, Katsaliaki & Taylor 2010; Luke & Stamatakis 2012), consistently growing in numbers and areas of investigation. This reflects the complex and dynamic nature of healthcare systems. In particular, the ability of SD to deal with *dynamic complexity*, the term introduced by Sterman (2000), is valuable when studying the subpopulations with different demands (Diaz, Behr & Tulpule 2012), the diverse stakeholders with conflicting policy aims, and the unclear ramifications of non-trivial planning decisions (Hoard *et al.* 2005).

The applications of SD in healthcare may be grouped according to level (national, regional, unit), type or phase of decision making (strategic and policy, tactical or operational management), or healthcare-related issues (prevention, population health and epidemiology, patient flows and healthcare delivery). In the field of ER, system dynamics may be used: (a) in more general emergency response models dealing with pre-hospital aspects of acute health care within a region, such as models of hospital-based emergency medical care delivery in a single emergency unit or (b) in a hospital-wide complex system including relations with wards and other hospital units.

A well-known approach by Brailsford *et al.* (2004) employs a whole-system perspective to study the causes of increasing emergency demand in the region of Nottingham, England and to investigate the ways in which patient flows and system capacity could be improved. Taylor & Dangerfield (2005) used two cases of a shift in the location of cardiac catheterization services to explore potential effects of alternative policies on demand for services. A conceptual framework of SD use for modelling mass casualty hospital preparedness in rural areas, seen as a community-wide effort, was formulated by Hoard *et al.* (2005).

More SD models have been formulated for the second group of ER problems, i.e. to investigate patient flows in hospital emergency units in the context of waiting times and bed capacity. For example, Lane, Monefeldt & Rosenhead (2000) explored relations between ER waiting times and changes in an ER bed capacity and Vanderby & Carter (2010) analysed additional ER performance factors like changes in personnel capacity, re-routing patients schemes, and increased arrival flows. A general approach to analysing ER performance was presented by Wong *et al.* (2012), who developed a conceptual model of the relations between ER and internal medicine. The authors have also elaborated a taxonomy of issues confronting hospital management with changing demand due to population ageing and healthcare evolution (e.g. shift from inpatient to outpatient settings or higher acuity and complexity of care). Demir *et al.* (2014) analysed a specific type of emergency demand, namely demand for neonatal care, and in-hospital patient flows in neonatal care units primarily for understanding of the behaviour of the complex system and informing the process of decision making and policy design.

4 PROBLEM STRUCTURING

4.1 System Description

The study was conducted in the Wrocław Region (WR), which is part of the Lower Silesia, the fourth largest region in Poland. The WR encompasses 9 districts: the capital of Lower Silesia (Wrocław) and 8 districts that are close to the capital. In 2010, the WR's population comprised approximately 41.11% of the Lower Silesian population. The AU/EWs located in the WR serve the inhabitants of the region in addition to patients from other Lower Silesia sub-regions and citizens from other Polish provinces. Individuals who reside in the WR may receive emergency treatment from the AU/EWs located in the WR and the AU/EWs located in other Polish sub-regions.

During the first stage of the study (Mielczarek 2013; Mielczarek 2014) we used DES modelling approach to forecast the level of emergency services that should be contracted by NFZ for the following year to cover the forecasted demand for emergency medical treatment in the WR. We then assumed that the population demography parameters were stable and aspects like migration, birth and death rates, average expected lifetimes, and morbidity factors did not influence the volume of ER patients.

The general concept of the hybrid DES-SD model is shown in Figure 1. The DES model captures three geographically related sources of emergency patients for direct admission to one of the AU/EWs located in the WR: flow no.1 - arrivals from the WR, flow no.2 - arrivals from other subregions of Lower Silesia, flow no.3 - arrivals from other Polish provinces. One output flow (no.4) simulates the WR patients who select the treatment outside the WR.

The model presented in this study attempts to find the relationship between the demographic changes observed over long period within the WR population and the number of patients arriving to AU/EWs located in the WR (flow number 1 in Figure 1).

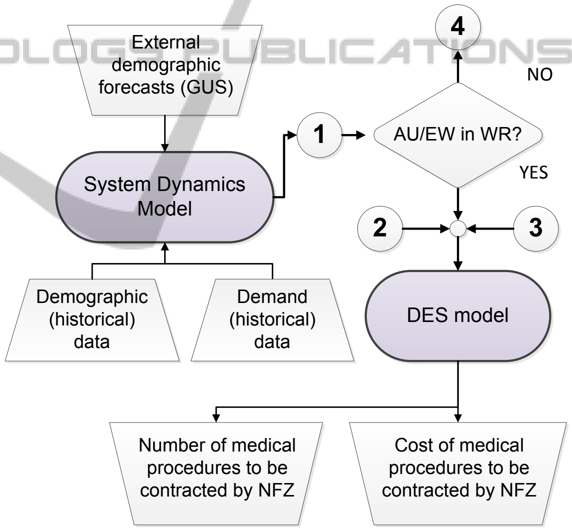

Figure 1: The general concept of the hybrid DES-SD model.

4.2 Model Overview

The basic causal structure of the system dynamics model built in ExtendSim software is shown in Figure 2. The general graph features only the main pathways by which the WR population influences the volume of demand for emergency services. At the core of the model is the aggregate population stock describing the demographic changes observed within the WR population. The detailed age pyramid model is presented in Figure 3 and discussed in the next section (4.3). Emergency needs of the WR population are covered by the AU/EWs situated in the WR (stock named "ER patients in WR") and the AU/EWs located in other Polish sub-regions (stock named "ER patients outside WR"). The size of the WR population is not, however, the only predictor of emergency attendances to AU/EWs. Patients with certain diseases or particular health problems (e.g., cardiac patients) may significantly increase the number of emergency cases ("epidemiological factors" in Figure 2). Because of the national health system regulations, it is not uncommon that some acute patients consider hospital AUs as alternatives to general practitioners, which increases the number of non-emergency cases treated by the emergency departments ("system related factors" in Figure 2). Patients living outside of the WR are free to choose a hospital in the area and therefore the stock describing the emergency services delivered by the WR providers ("ER patients in WR") is affected by another flow named "other patients treated in WR".

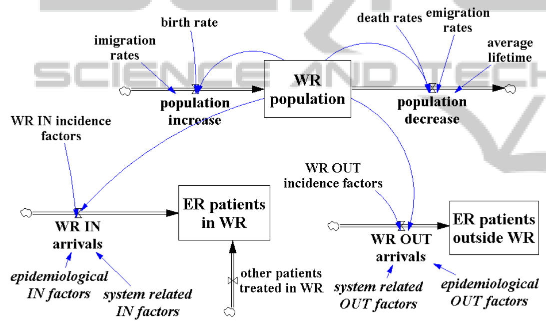

Figure 2: Overview of model structure, showing quantitative (roman) and qualitative (italics) input factors.

4.3 Dynamic Aging Chain

The initial data analysis revealed that, in terms of generating demand for emergency services, the population is not homogenous, and the different age groups have a different share in the global number of emergency presentations (Table 1). We used two aging chains according to each gender (Krejci, Kvasnicka & Svasta 2011) with five age groups in every chain (Figure 3). These age groups were chosen because of the compatibility with the data sources used for parameter quantification.

Each cohort (stock), except for the last one, of the female aging chain presents a state variable with two input and three output flows. The input flows are: births (cohort 0–4) or maturation from the previous age group (cohorts 5–19, 20–39, 40–59), and immigrations. The output flows are: emigrations, deaths, and maturation to the next age group. The last cohort (60+) has two input flows: maturation from the age group 40–59 and immigrations, and two output flows: emigrations and deaths.

The aging chain for males differs from the female chain in that the birth input flow depends on the number of female 20–39 cohort.

The initial values of every cohort match historical conditions. During simulation, the state variables change at equal time intervals based on the integrated (no delay) mode (ExtendSim 2014). This means that all input and output flows that are connected to the particular stock (cohort) are aggregated into one dynamic object and this resultant flow instantly increases or decreases the number of individuals in the cohort.

Table 1: Percentage share of the age groups in the total number of emergency cases. Historical data 2011.

Age group [years]	Female [%]	Male [%]
0–4	8.5	10.5
5–19	13.5	17.2
20–39	25.7	29.3
40–59	21.3	22.3
60+	31.0	20.8
Total	100.0	100.0

The formulas used to model input and output flows are briefly described in Table 2: this is usually the function of the given population cohort and the appropriate rate indicators.

Table 2: Formulas used to determine the flows' equations.

Flow	Function of:
births	- quantity of *F 20–39* women cohort - fertility rates
deaths (0–4, 5–19, 20–39, and 40–59)	- quantity of population cohort - mortality rates
deaths (60+)	- quantity of the population cohort - the average life expectancy for the female/male at the age 60
emigration	- quantity of population cohort - emigration rates
immigration	- quantity of population cohort - immigration rates
maturation	- quantity of population cohort - full time within cohort

The simulation begins in 2007 and, until 2012, the parameters have been set to values calculated on the basis of published historical data (GUS 2014). Beyond the year 2012, the exogenous variables can not be based on survey data and are estimated using historical data and forecasts published by GUS (2014).

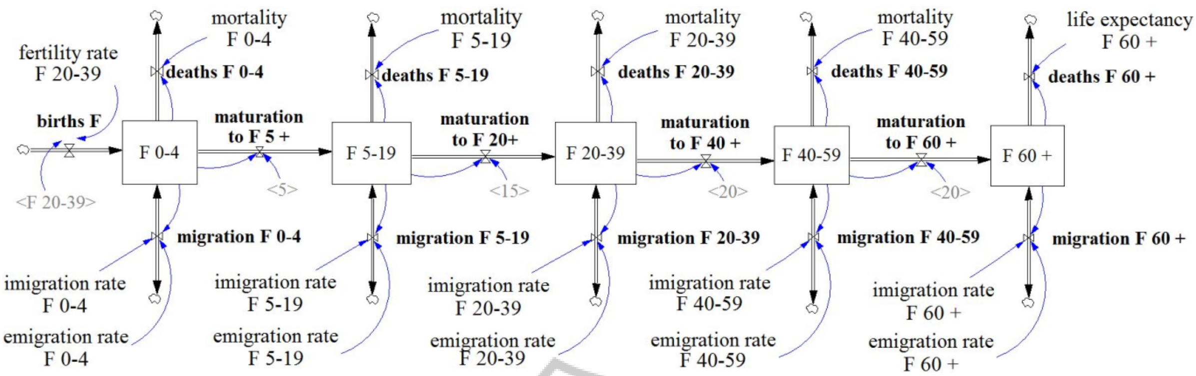

Figure 3: Female aging chain with five cohorts.

Some parameters remain on the same level as observed for 2012 (e.g. migration rates), some slightly increase (e.g. female/male birth rates), and some very slowly decrease (e.g. female/male death rates). More rapid decrease is forecasted for the newborn death rates. The average life expectancy at the age of 60 linearly grows to 24.51 in the year 2035 for a male, and for a female to 28.89.

4.4 Emergency Demand

Every population cohort influences two flows of ER demand: the main flow (Figure 2), which is served by the WR providers ("emergency arrivals inside WR"), and the additional flow, which is served by the ER providers situated outside of the WR ("emergency arrival outside WR").

Figure 4 shows an overview of the essential causal structure for the female ER sub-model. The single cohort of females simulated in the population sub-model influences the number of emergency cases classified into the particular age/gender related ER stock. Every ER stock is also supplied by the input flow of acute patients living outside of the WR. The sum of all ER stocks determines the number of emergency cases treated in the WR.

Data for the emergency demand analysis were obtained from the NFZ regional branch in Wrocław for the years 2010–2011. Two basic data sets were analysed. The first included information on 183,517 emergency visits by patients residing in the WR who arrived in AUs/EWs located in the Lower Silesia area. The records from the second data set included 201,636 patients with any residence codes registered in AUs/EWs deployed in the WR. Based on these data sets the rate-flow parameters were estimated.

The model also incorporates two other groups of factors affecting the ER flow rates that may be directly amenable to policy intervention: the morbidity trends and the health system related parameters. The morbidity flow-rate drivers reflect the epidemiological trends, as forecasted for the WR population, that may affect the total volume of ER demand. For example, it is expected that the number of emergency cases generated by the youngest population cohort may decrease because of the continuous decline observed in the number of cases of the digestive system acute infectious diseases. Conversely, hospitalization rates due to cardiovascular diseases are systematically increasing, particularly among the oldest population groups. The second group of flow-rate drivers is closely related to health system regulations and the health policy strategy. The limited access to primary care providers (PCPs) manifesting itself in long waiting times to receive specialist care, results in the significant increase in the number of non-acute patients arriving to AU/EWs. The concept of the policy-related flow-rate parameters is based on the risk indicators that intensify or weaken the basic level of the ER demand generated by the WR population.

5 SIMULATION EXPERIMENTS

5.1 Model Testing

The simulation output measures are: the number of the WR patients treated by the AU/EWs situated in the WR and the number of the WR patients served by the AU/EWs situated outside the region. Both measures are calculated for the whole calendar year.

The simulation starts in 2007 and in the baseline scenario we assume that no changes occur in policy related flow-rate factors (these are invisible for the simulation model and they do not influence the model's behaviour).

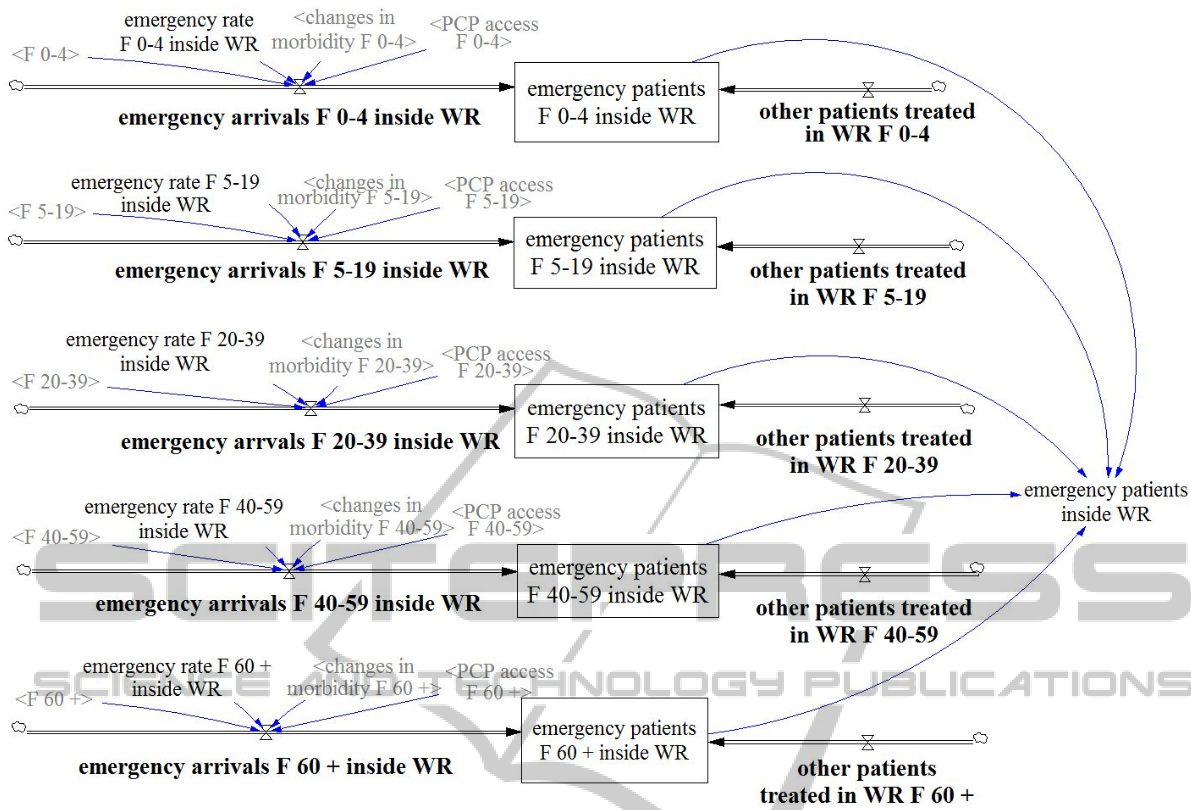

Figure 4: Female ER demand served by the WR providers.

Validation was performed in two phases. First, the population sub-model was tested for fit against 2007–2012. Figure 5 presents two age pyramids for 2012: the dark coloured pyramid represents the distribution of the WR population based on the historical data published by GUS (2014). The light coloured pyramid represents the simulation data. Mean absolute percentage error shows that simulation model provides good results for the estimation of the WR population. For particular age cohorts the value of the indicator ranges from 1.72% to 11.53% (male population) and from 2.58% to 9.24% (female population).

Second, to determine whether the model properly represents the volume of emergency demand, we compared model output to the historical data collected for the WR in 2010–2011. The results (Table 3 and Table 4) show how closely the simulated output lies to the actual reported data. We observe a slight underestimation in the simulation results.

Figure 5: The comparison of the age pyramids of the WR population built from the historical (dark colour) and simulation (light colour) data.

Table 3: The comparison of the simulation and the historical number of ER patients treated inside the WR.

Year	Historical data	Simulation	Difference
Female patients			
2010	89 979	87 814	-2.47%
2011	92 284	89 727	-2.85%
Male patients			
2010	89 777	87 124	-3.04%
2011	92 094	89 027	-3.45%

Table 4: ER patients treated outside of the WR. The comparison of the simulation and the historical data.

Year	Historical data	Simulation	Difference
Female patients			
2010	9 929	9 499	-4.53%
2011	1 0182	9 682	-4.93%
Male patients			
2010	11 951	11 392	-4.91%
2011	12 412	11 732	-5.80%

5.2 What-if Scenarios

Four "what-if" scenarios were devised to illustrate the potential of the suggested approach. The simulation begins in 2007 and runs until 2035, with time step equal to 0.01 (of the year).

Scenario 1: Birth rate increase

The first scenario simulates the birth rate increase. According to some cautious forecasts, the new parental leave regulations may reverse the actual unfavourable trend and cause a noticeable increase among the youngest population. We assume that starting from 2015 the birth rates (both in male and female population) will increase by 0.2% and this trend will be maintained during four following years (until 2019). Then, the birth rates will return to the previous values.

Scenario 2: Demand increase in the oldest cohort

The second simulated scenario considers an increase of acute cases due to morbidity rates growth resulting from the diseases of the circulatory system in the oldest population. We assume that starting from 2015, the increased morbidity rates (in 60+ male and female cohorts) will generate 5%, 10%, 15% and 20% more emergency calls from the WR oldest population than is observed today. Then, the morbidity rates will remain on the increased level.

Scenario 3: Demand decrease in all age groups

The third simulated scenario features a reduction in the number of emergency calls as a result of changes in the global health policy. The common problem of long waiting queues (often measured in months or even years) for a consultation with a specialist doctor, increases the volume of non-emergency patients' arrivals at AU/EWs. We tested the consequences of some solutions that would lead to a global reduction in the number of acute cases.

Scenario 4: Population projections

The fourth scenario uses assumptions formulated in the long-term population projection prognostic document constructed by GUS (2014). One of the most optimistic forecasts published in the document, foresees that starting from 2013: fertility rates will increase, mainly because of social security system reform; a favourable drop in death intensity will be observed; an average life expectancy in 2035 will be similar to the rates obtained in the developed countries 17 years earlier; a mild decrease in the migration streams will be observed.

5.3 Preliminary Scenario Comparison

Figure 6 shows a comparison of the first three scenarios in terms of the impact on the total number of emergency cases to arrive in the WR over time. The greatest influence on acute demand has the increased number of diseases of circulatory system in the oldest population (Scenario 2). The aging of the population and higher morbidity have amplified the total demand and caused an increase in the number of emergency patients in 2015. However, even if the morbidity rates ceased to rise after 2019, a more intense increase in acute demand would be observed as compared to the baseline. Higher birth rates will have a slight impact on the number of emergency patients (Scenario 1). The simulated decrease in the number of non-emergency arrivals at AU/EWs, achieved through policy regulations (Scenario 3), will reduce the acute demand proportionally.

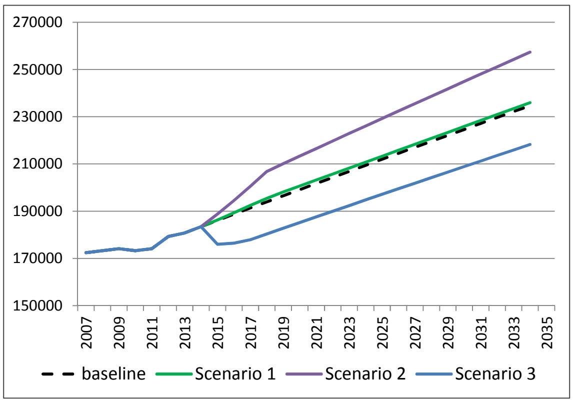

Figure 6: Impact of "what-if" scenarios on the emergency arrivals in the WR.

The favorable changes forecasted in the optimistic prediction of the population projections (Scenario 4) suggest a slight and continuous growth in the number of ER patients (Figure 7). These preliminary results show that because of the increased fertility rates and extended life expectancies the demand for hospital emergency services will systematically grow.

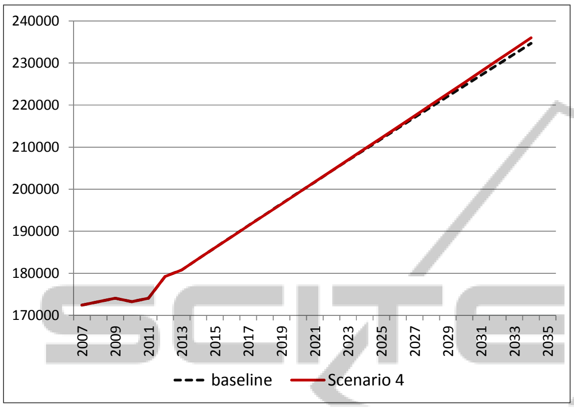

Figure 7: Impact of long-term population projections on the emergency arrivals in the WR.

Figure 8 compares the development of the age pyramid of the WR population between 2012 and 2035, as predicted by the simulation model, according to assumptions formulated in Scenario 4.

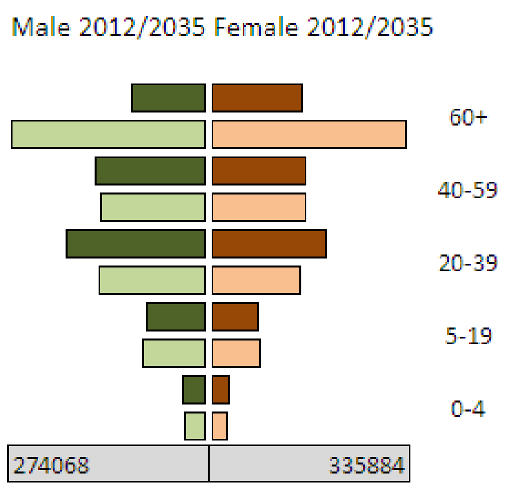

Figure 8: The comparison of the age pyramids of the WR population built from the 2012 historical (dark colour) and 2035 simulation (light colour) data.

The simulation results for the year 2035 indicate a decrease in the number of individuals within three age groups (0–4, 20–39 and 40–59) in comparison to 2012. Two age groups (5–19 and 60+) will however experience the observable growth in the number of persons. In particular, the oldest cohort will have to face a rapid increase for both gender groups. The number of women aged 60 and over will be higher by 115.8% and the number of men – by 161.3%. The total number of population in 2035 will increase by 21.5% in comparison to 2012.

The predicted changes in the structure of the WR population will significantly influence the number of ER patients served by AU/EW situated in the WR (Figure 9 and 10). A detailed analysis of the age groups requiring acute services shows that the total number of patients not older than 60 will decrease but the increased number of individuals from 60+ age groups (men and women) will dramatically raise the overall demand. Those older than 60 are responsible for the continuously growing share of estimated ER needs. In particular, in 2035 this group represents almost half of the total needs (Table 5). Since older patients usually require the more costly procedures during the ER treatment, the overall cost of emergency services in 2035 is expected to be much higher than in 2012.

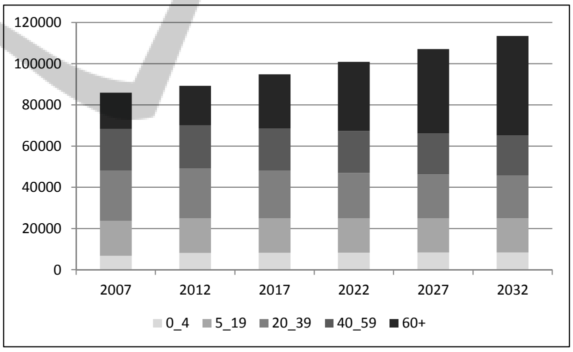

Figure 9: Number of ER patients (men) classified according to five age groups in the years 2007 - 2035.

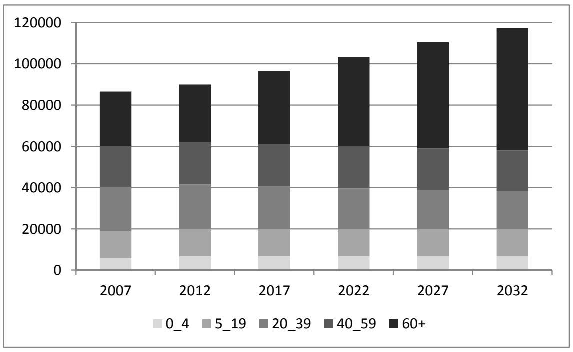

Figure 10: Number of ER patients (women) classified according to five age groups in the years 2007 - 2035.

Table 5: Percentage share of the age groups in the total number of emergency cases. Simulation data 2035.

Age group [years]	Female [%]	Male [%]
0–4	3.7	4.3
5–19	11.0	12.8
20–39	20.2	21.8
40–59	21.3	21.6
60+	43.8	39.5
Total	100.0	100.0

6 DISCUSSION AND FUTURE DIRECTIONS

The model presented here extends our understanding of the relations between the ongoing changes in the WR population demography and the volume of hospital emergency needs expressed by patients arriving at AU/EWs situated in one of the Polish regions. The simulations suggest that the NFZ will have to tackle the problem of the growing demand for hospital ER services over the coming years. Although we have explored only a few of the demography related factors, it is clear that the more unfavourable scenario (e.g. Scenario 2: the increased morbidity in particular cohorts) will amplify the ER presentations.

Different age-gender segments of the population have different shares among the total number of ER patients. The significant delays between the initial impulse in one cohort (e.g. the increased fertility rates) and the resulting changes in the subsequent cohort (e.g. the growth in a number of young men generating the highest volume of acute cases) make it difficult to formulate credible prognoses. Therefore, although the potential direction of the forecasted incentives is foreseeable, the magnitude of the expected results is unknown. The simulation model described in the paper aims to contribute to filling this gap by studying the consequences of the population dynamics on the emergency needs expressed by patients arriving to AU/EW in the region.

This paper describes work in progress and we plan to study the relationships between the demographic factors and the ER presentations to a greater extent. For example, the shift in the mean age at childbearing and relationship formation to higher age groups will change the structure of the age pyramid and, consequently, the level of cohort related emergency needs. Further, the interesting but not yet empirically examined influence of such qualitative aspects as investigation of the policy related incentives is also planned. Facilitating access to primary care and encouraging a shift to PCPs could decrease the number of patients arriving to AU/EWs.

The study presented in this paper also needs a stronger empirical analysis of the qualitative parameters. Future work will focus on performing sensitivity analyses to determine the impact of uncertainty surrounding parameter values. We plan to use system dynamics approach to formulate valid demand forecasts that could be used by a discrete simulation model to assess the volume of services to be contracted by NFZ in particular AU/EWs in the region.

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