A SYSTEM DYNAMICS MODEL FOR THE DIABETES PREVALENCE IN AUSTRIA

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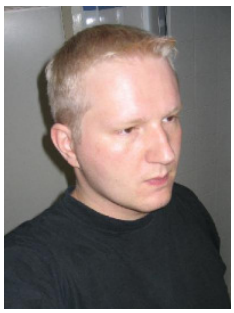
Abstract

In this paper we present a System Dynamics model for the incidence of type-2 diabetes in Austria based on a model developed by A. Jones, J. Homer et al. [1] for the United States of America. The main influencing factors incorporated in the model are obesity, age and disease management. This model is developed further to better represent the health care organization in Austria as well as to include a distinction by sex. While most control circles are very similar to the USA model the input parameters differ radically, making an adaptation necessary. This results in large deviations in the disease prevalence relative to the total population. A thorough stability analysis is carried out and the question of sensitivity to input parameters variation is investigated. A comparison with available historical data shows the applicability on the real world system. A test run is made and compared with the standard scenario of no change in health care politics after 2007. This test run is in accordance with the WHO recommendation of half an hour of physical exercises per day and it is shown to be effective in the prevention of type-2 diabetes mellitus. Further developments and test runs are suggested.

Keywords: system dynamics, health care modeling, socioeconomics, complex data, large scale modeling.

Presenting Author's biography

Peter Kristöfel. He is a theoretical physics master who has also earned a degree in mathematics. With an interdisciplinary background he has experience in the application and the development of numerical methods. Past work included high performance computing and classical and quantum chaos. Current work focuses on simulation and modeling techniques.



1 Introduction

Diabetes mellitus (DM) and its complications are one of the most challenging topics in public health care. Consequent diseases include neuropathy along with the risk of gangrene and a later amputation, nephropathy that can lead to obligatory dialysis as well as to the necessity of a kidney transplant and retinopathy with the danger of premature blindness. With a prevalence of 25 million people in the European Union and 60 million people at risk of developing pre-diabetes, diabetes is a major chronic disease responsible for 5 to 10 percent of the total health care costs [2]. The WHO expects a rise in diabetes prevalence of 37 percent from the year 2000 to the year 2025 [3]. The question is how to best manage this serious threat to public health.

One way to find an answer is to employ System Dynamics (SD) with it's a very broad range of applications in natural, economical, technical and social sciences. SD models are perfectly suited to test different policies of intervention in simulations and therefore are a powerful tool to help finding the best strategies.

We adopt a SD model, commissioned by the Center for Disease Control and Prevention (CDC) in the USA and developed by A. Jones, J. Homer et al. [1], which has been successfully applied to reproduce the historical available data of the last two decades. The structure of the model arises not only from the progression of DM as a chronic disease but also from the available data. We adopt the model to the Austrian data set and enhance it to include a distinction by sex since different policies may become necessary.

The structure of this paper is as follows: In section two we try to answer the question why using SD to develop a model for the diabetes prevalence makes sense. The main stocks and flows in this model are described in section three. Section four discusses the available input data and methods to handle them. Section five deals with the main influence factors: obesity as a function of caloric intake and consumption, age and disease prevention and control. A stability and, at least to some extend, a sensitivity analysis is carried out in section six. Results for Austria are given in section seven. The last section will summarize our findings and propose testing schemes and further future work.

2 Modeling motivation

Chronic diseases are widespread above all in our aging affluent society. Approximately one third of the total population suffers from chronic diseases and with increasing age the percentage is rising steeply. Already more than one half of the people above 60 suffer from at least one chronic disease. Therefore these afflictions are responsible for a great part of the health care costs, outstripping the costs of accidents and acute diseases combined. According to all estimates chronic diseases are going to increase further [6].

Besides the socioeconomic importance, chronic diseases sport several features which suggest a SD treatment:

1.) All health care officials, including doctors, politicians, patient associations and other medical staff, recognize the threat and agree that measures on a population-wide, system-wide level have to be taken to reduce chronic diseases and their consequences. But most programs sport conventional analytical methods by which each aspect of a complicated disease control strategy is addressed and evaluated separately. The advantage of SD here is that one gets a global picture where all influencing factors are incorporated and act together.

2.) Chronic diseases involve long time scales. There are long delays between causes and health consequences making short term analysis methods unsuitable. Three prevention levels, of which each can require dozens of years of treatment, are distinguished: primary prevention to avoid the onset of an affliction, secondary prevention to avoid chronic development and harmful consequences and tertiary prevention to avoid the loss of functions [4].

3.) For every prevention level many different policies are available. Primary prevention includes behavioral and socioeconomic measures like improving lifestyle, working and living conditions, information, education and many more. Secondary prevention focuses on precaution and early detection. And finally elements of the tertiary prevention are accessibility to the medical treatment, improvement of compliance and empowerment. All these measures together with quality control are elements of a process-based disease-management approach. SD now gives the opportunity to test different approaches and policies simultaneously and observe the respective outcome.

Finally diabetes mellitus is the prime example of a chronic disease. It is researched well enough so that the main risk factors are known and that much input data is available.

3 The core model

Of diabetes mellitus only the risk for type-2 diabetes, which is responsible for 85 to 95 percent of all cases, is reasonably influenceable. Since type-2 DM is still very seldom for juveniles we restrict ourselves to the adult population. The steep rise of people with DM from 1995 to 2000 is not only due to a higher prevalence but also due to better and earlier diagnosis. This has also consequences for the model structure: In

Figure 1 we present the population stocks and flows in our model. We distinguish seven different population stocks arranged in four groups. The first group consists only of one stock: the healthy adults who have a normal blood-glucose level. The other groups each consist of two levels, the diagnoses and the undiagnosed ones. The second group is the population with pre-diabetes. These are people with an increased blood-glucose level but not yet having developed full diabetes, which constitute the third group. In the last group are people who not only have diabetes but are also stricken by consequent diseases.

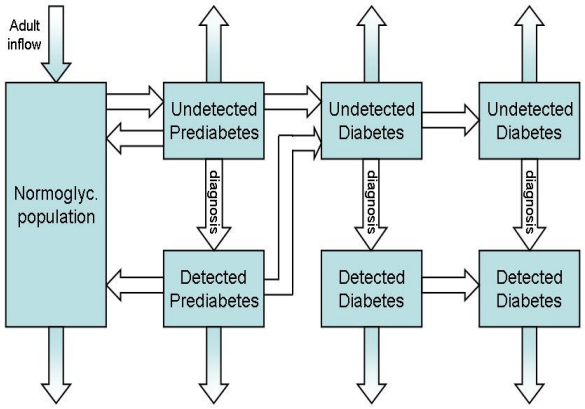


Figure 1: The main stocks and flows of the model

Let us now examine the flows more closely: There is only one inflow of healthy adults into the fist level, while people may die out of every level. This inflow is given as a time series input by statistical predictions. The different death rates are affected by the fraction of obese people of every stock, which is calculated in our model, as well as by the fraction of elderly people, which is again given as a time series. The basic assumption is that the relative rates of people with a risk factor compared to people without it remains constant in the respective group. Written explicitly

$$\frac{\mathbf{P}(\text{death} \mid \text{elderly})}{\mathbf{P}(\text{death} \mid \neg\text{elderly})} = const.$$

$$\frac{\mathbf{P}(\text{death} \mid \text{obese})}{\mathbf{P}(\text{death} \mid \neg\text{obese})} = const.$$

hold true for every group, where $\mathbf{P}(a|b)$ denotes the conditional probability of factor a under condition b. If DM is already detected than also the control of the disease, the "disease management", is influencing the death rates. With suitable initial values the dynamic death rates can then be calculated.

The flows between the different stocks are characterized by the following assumptions: While people with pre-diabetes can still recover, there is no way to cure DM after its onset. DM is a chronic disease after all and once complications occur the damage is dealt and cannot be undone. The onset of pre-diabetes and DM occur unobserved, while complications can also arise even if under medical supervision. All transition rates are affected by the elderly and the obese fractions of the respective populations. The progression rates (the horizontal untitled ones) of the detected populations can be influenced by the clinical management, like prevention measures and compliance. The detection rates (the vertical ones) are more difficult to describe: they are first order exponentially delayed functions of the progression rates as well as the testing frequency and the sensitivity of the tests. Time dependent input data enter in several places of DM detection and control incorporating different possible health policies.

4 Data basis

The original model is very complex, allowing for nonlinear behavior. There are over 134 different input parameters and not all of them can be measured directly. It is therefore necessary to estimate some of the unmeasured input parameters so that the output reproduces available historical data. This is the reason why we start the simulation in 1980 and continue it till 2050. The model for the United States of America incorporates qualitative statements in their parameter estimation and use a partial-model-tuning approach. In short the tuning of uncertain parameters is done manually but applied to the smallest possible piece of structure and the smallest possible cluster of parameters given the configuration of available time series data.

Since the available data are very different in Austria compared to the US we will look at some points in detail now. Where data are available we of course use them directly or use them to calculate the necessary input parameters. Examples are the future population for every year as describes below and the initial death rates from the life expectancy.

Another point is that the available data originate from different years, like data recorded only since a certain starting date or the progression of classification standards. For the parameters which remain constant over time, like the ratio of the death rates above, this constitutes no problem. Where appropriate data are available the assumption that they stay constant is tested. In the other cases we have reason to believe in the validity of this assumption since the model worked for the US.

Where no data from Austria are available we use data from nearby countries, like Germany or the United Kingdom, or we use the input parameters from the US model. This is justified since all these countries belong to the same western industrial culture area. Therefore it is expected that the parameters are almost the same as in Austria. Additional confidence is provided by the fact that parameters for the US model have already been verified [1].

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And finally the specific situation in Austria makes some parameters unnecessary or completely different. One difference to the USA model arises from the fact that everyone in Austria has access to health care and can afford the necessary medicaments and treatments thanks to the compulsory insurance system and free social healthcare. The second difference is that the costs of DM and consequent diseases are simply not comparable.

One major difficulty encountered when modeling diseases in general is the estimated number of unreported cases. Several studies are available on this topic (c.f. [7] and references therein). Our findings are in fairly good agreement to the WHO estimates of a current DM prevalence of 5 to 7 percent [3]. The exact number of cases is not to be taken intimately, but this isn't our goal anyway. In the application we want to compare different policies of health care management against each other.

For the analysis in this paper we use data for Austria. The quality of the data is good and many input parameters are available, especially with respect to the distinction by sex. This distinction is made by running the model twice with different input parameters and then adding up the respective results.

5 The main factors of influence

We have already identified the most important influencing factors: age, clinical management and obesity. The age enters through the fraction of elderly people. The adult population, including people of age 20 and above, is given by a time series calculated from the demographic development taken from [5] (from where the online data tables were exported). The fraction of elderly people is calculated as the fraction of people age 65 and above compared to the adult population and can be seen together with the adult population in Figure 2. The calculation of the values for each year is done by a spline interpolation of order 3 of the available data. Note that the results do change less than one percent if we use linear interpolation instead.

The disease management allows adjusting the following time dependent input parameters: the testing of high-risk patients, the testing for and the monitoring of pre-diabetes, the ability to self-monitor the blood glucose level and the ability to adopt a healthy lifestyle. For the calculation of the standard scenario the historical values of these input parameters are taken from [5,6,7,8] and are assumed to stay constant after 2005.

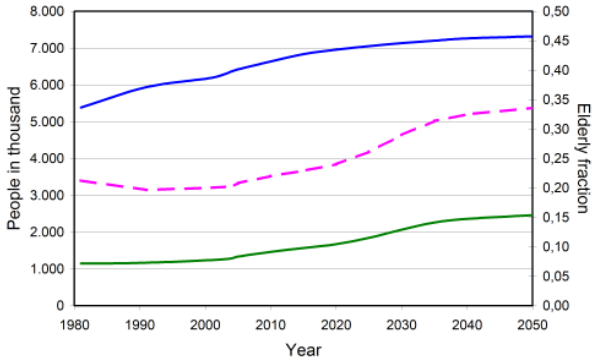

Figure 2: Adult (upper solid line) and elderly (lower solid line) population and the fraction of elderly people (slashed line, right scale) in Austria from 1971 to 2006 (data) and prognosis till 2050.

Finally the obese fraction of the population is calculated dynamically in our model. Figure 3 presents the controlling feedback loop which governs the body-mass-index (BMI) in dependence of the calorie intake and consumption. Here lies a difference to the original model: While the physical activity calories were given directly as a time dependent input variable in the US model we don't have these data available for Austria. Instead we use the physical activity level, which is a multiple of the basal metabolic rate, as given in [6]. Finally this control cycle is also a reason why we only study adults: The formulas used are valid only for adults and we automatically exclude adolescence effects on the BMI.

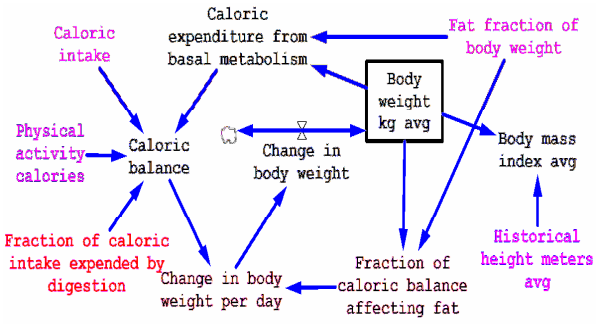

Figure 3: BMI-feedback cycle, details are found in [1].

The fraction of the obese population is then a well known empirical function of the average BMI. With this variable the obese fraction of the population with a normal blood glucose level can be calculated and via a smoothing process the fractions of obese people in the other stocks.

6 Stability and sensitivity analysis

Qualitatively this type-2 diabetes mellitus SD model is very complex and therefore there is no chance to analyze the stability of the system analytically. However, there are some qualitative considerations which can be made:

The first has to do with the stocks and flows structure: the only inflow in the system is the adult population (c.f. figure 1). Nowhere else in the system new population can enter, the people are only allowed to die out of the system. Therefore the number of people in the system is bounded and no unlimited growth can arise. Secondly all the flows are time-delayed, so we can expect that the system responds smoothly to discrete changes of the input variables and no instantaneous depletion of a level can occur.

And finally a first order analytical approximation for the effect of input parameter changes of sub-systems can be made. However, this is not sufficient for the analysis of the stability of the system due to the occurrence of feedback loops: the errors have a feedback on themselves and therefore they may accumulate in a geometric series or even worse. Since there is no chance to solve this problem analytically we have to investigate the stability and the sensitivity to input parameters numerically.

As a quantitative analysis two things were done: firstly each input parameter was changed individually. By changing each input consecutively by ±20% the output variables always changed by less than 10%, except when changing the initial population levels. The change was done linearly around the initial value, as long as the values where in the allowed range (e.g. no probabilities greater than one). This is a first indicator that the system is stable and that, with the exception of the initial population levels, the system is not very sensitive to parameter changes. This is true especially in the long time behavior, when the time dependent input parameters do not vary any more (c. f. the standard scenario).

Secondly the Ljapunov exponent was calculated while some input parameters were varied. The Ljapunov exponent measures how fast the trajectories of different initial conditions separate (positive exponent) or converge (negative exponent) in phase-space with time. The definition of the maximal Ljapunov exponent λ for continuous, differentiable systems is

$$\lambda = \lim_{t\to\infty} \frac{1}{t} \ln \left| \frac{\delta Z(t)}{\delta Z(0)} \right| ,$$

where t is the time and $Z(t)$ is the trajectory in phase-space. But since we do not know this movement through phase-space analytically we had to work numerically. The numerical calculation is more difficult and was done in the following way:

A Monte-Carlo sampling of the System Dynamics model was performed: some of the input parameters where varied randomly at the same time. The variations followed a Gaussian distribution with a standard deviation of 20% around their initial values.

This was done for 100 different input parameter combinations and the respective results have been calculated. The discrete Ljapunov exponent can be calculated as

$$\lambda = \lim_{N\to\infty} \frac{1}{N} \sum_{n=0}^{N} \ln \left| \frac{\partial}{\partial y} f(y(t_n)) \right|$$

Since we do not know the analytical derivate of the time evolution function $f(y(t_n))$ with respect to the phase-space variables $y(t_n)$ we need to approximate the differential quotient through

$$\frac{\partial f}{\partial y} = \frac{f(t_{n+1}) - f(t_n)}{f(t_n) - f(t_{n-1})}$$

This approximation is valid since the values for the time step t_{n+1} are calculated from the values of the previous time step. The approximation is quite good as long as the denominator stays away from zero, which is luckily the case. If the simple finite difference quotient would be calculated instead, a wrong result would be obtained since the effect of the phase-space velocity of the system would be excluded.

Now two kinds of averaging have been done:

1. The mean of all runs has been taken and the Ljapunov exponent from it has been calculated and

2. the Ljapunov exponents for every run have been calculated and averaged afterwards.

For the test runs from Figure 4, where all time independent input variables with exception of the initial population levels have been varied, the respective results are $\lambda_1 = -0.0377$ and $\lambda_2 = -0.0373 \pm 0.007$. All of the individual exponents in the second case are negative and the ±0.007 is the standard deviation. These Monte-Carlo averaged Ljapunov are very similar, their difference is of the order of the standard deviation. For all kinds of variations of the input variables and parameters the Ljapunov exponent turned out to be negative although small (typically between -0.02 and -0.1). There turned out to be no significant difference if 1.000 instead of 100 different parameter combinations were used.

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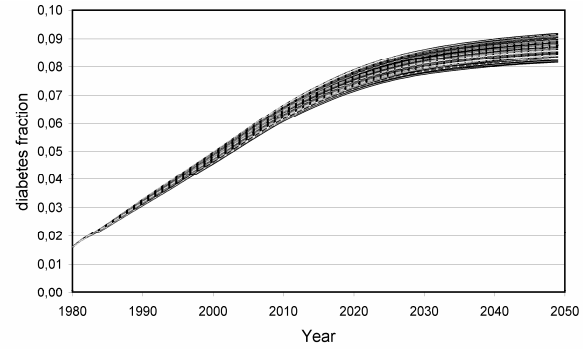

Figure 4: The diabetes fraction of the adult population for 100 different parameter values.

We can now interpret these results: although a variation in the initial conditions leads to a larger difference in the end than in the beginning the system turns out to be stable. The system is also not very sensitive to a variation of individual parameters. The conclusion is that the system is quantitatively dynamically stable in accordance with the qualitative expectations, as long as the input data does not leave the compulsory bounds (like probabilities greater than one and the like).

7 Testing schemes and results for Austria

In this section we give the results for the development of DM in Austria till 2050. We also test different scenarios for the management of DM against the standard scenario that every parameter remains constant after 2005.

In Figure 5 we see the fractions of detected and undetected diabetes and diabetes with complications, where all input parameters except the adult population inflow and the fraction of elderly people remain constant after 2005. We see that the diabetes fraction of the adult population continues to grow until around 2025 and then becomes slowly saturated. The diabetes with complications fraction of the adult population shows a similar behavior. Almost all cases of DM with complications are detected. The same is true only for 70 percent of the uncomplicated DM population. The distinctive form of the undetected diabetes without complications curve between 1980 and 2000 is due to the beginning of the detection of pre-diabetes as a disease. The sum of all diabetes cases increases in a much smoother way.

As an example for a possible policy testing we give the results of the same test run with the difference that the physical activity level, which is in Austria somewhat below the recommended level [6], is, starting with 2007, increased over a time-span of 10 years to the recommended one. This is in accordance with the WHO recommendation that everyone should make half an hour of physical exercises per day. In Figure 6 we see the diabetes fraction of the adult population compared to the total of Figure 5 with the difference that people are going for a walk at moderate speed for approximately an hour per day from 2007 onwards (which corresponds to the recommended PAL increase). We see that the growth of the DM percentage stops after approximately three years and begins to drop afterwards. This time delay is of the same magnitude as the typical time delay constants occurring in the model. In the year 2050 the total diabetes prevalence has dropped about 1.5 percent. The absolute number of diabetes cases is however still increasing for a longer time due to an increase in the adult population.

This is especially relevant for the costs and e.g. the planning of health care institutions. This example could be incorporated in reality with relative low costs compared to the diabetes care costs.

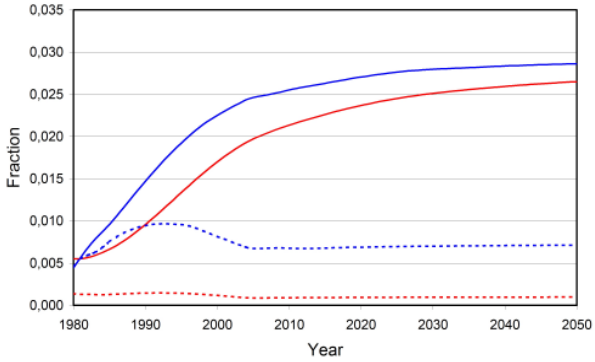

Figure 5: Detected (solid) and undetected (slashed) diabetes (upper lines) and diabetes with complications (lower lines) fractions of the adult population in Austria.

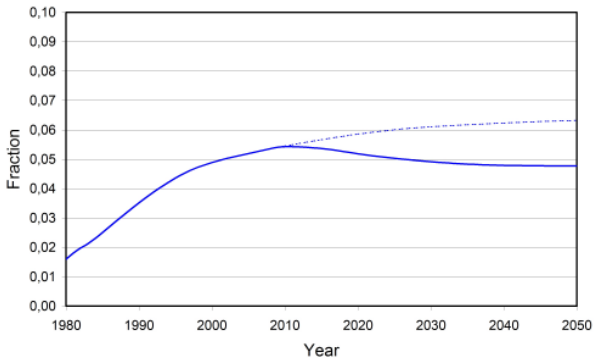

Figure 6: The diabetes fraction of the adult population when the PAL is increased from the current to the recommended level over the next ten years compared to the standard scenario (slashed line).

8 Summary and outlook

In this paper we have shown how a SD model for the DM prevalence in the US can be modified to fit the specific requirements and the available data in Austria. The stability and the sensitivity of the system have been analyzed. The WHO recommendation of half an hour of physical exercises a day has been shown to be effective to prevent type-2 diabetes mellitus.

Further work is on the way to compare more different health care schemes for Austria and to include a more detailed health care cost analysis.

From the applied side of SD the following case studies can be made: We can also simulate different regions of health care to analyze the west-east gradient of life expectancy and life style in Austria. Together with the Hauptverband der Sozialversicherungsträger and other public decision makers responsible for health care various policies may be tested. Especially interesting is whether different policies for men and women are useful. Ongoing studies to examine the disease management from prevention and early detection over lifestyle adjustment to compliance are suited to validate the predictions made by the SD model.

Future work may also include a combination with SD models for obesity

9 Acknowledgements

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