COMPARTMENT MODELLING OF OBESITY IN INHOMOGENEOUS POPULATIONS: PROBLEMS AND ALTERNATIVE APPROACHES

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Abstract

Introduction: Obesity is a chronic disease defined as the presence of excess adipose tissue and it is a national and also worldwide problem with a lot of consequences for health, like coronary heart disease, diabetes mellitus type 2 and even death. It is a very complex problem and to work against this epidemic, it is important to understand the mechanisms influencing this disease.
Methods: This paper is about different modeling approaches in the area of differential equations, Markov Models and System Dynamics Models found in the literature, their advantages and disadvantages.
Results: Some of the described models divide the population into sex, age or severity degree of the disease, which is important, since there is, for example a difference in the basal metabolic rate for persons with different age, sex and weight, but no model divides into all dimensions together. One alternative approach is proposed, describing an Agent Based Model that includes all dimensions when studying such a complex system. Advantages and disadvantages of the proposal in contrary to System Dynamics Modeling are shortly discussed.
Conclusion: When it comes to modeling complex systems it is necessary to make decisions about what is required to be displayed from the real world in our models.

Keywords: System Dynamics, obesity, Markov Models, Agent Based Modeling

Presenting Author's biography

Barbara Glock. She was born in Vienna on 5th of March, 1984, started school in 1990 and passed with distinction 2002 from secondary school. After that, she studied Technical Mathematics in Computer Sciences, which she will finish in the end of 2010. Her recent work includes her diploma thesis about a System Dynamics Modeling approach of the prevalence of obesity in Austria.

1 Introduction and facts about obesity

Obesity is a health concern of paramount importance in Austria and also worldwide. Doctors and Scientists finally think of obesity as a real disease and not, as done before, as a self caused state without any medical importance [1].

Obesity is measured by the so called Body Mass Index (BMI), which is calculated by dividing body mass m (in kg) through the square of body height l (in meters) as shown in Eq. 1.

$$BMI = \frac{m}{l^2} \qquad (1)$$

The main classification of the BMI, according to the WHO standard [2] is shown in table Tab. 1. The classification for children is measured slightly different with so called percentiles.

Tab. 1 BMI classification: The BMI is divided into 4 main categories of weight classification for adults.

Classification	BMI
underweight	<18.50
normal weight	18.50 – 24.99
overweight	25.00 – 29.99
obese	≥30.00

This classification is adequate in the majority of cases, but in some circumstances, it is better to divide the category *obese* in two, because, as it is in Austria, it is standard to do some surgeries like gastric bending or prescribe some medication only to people with a BMI ≥40.00. As a result most data one can get is further subdivided in category *obese* and *severely obese* with BMI 40 as a cutting point. In Austria there were 35.3% of the population with a BMI 25 – 30 and 12.4% with a BMI ≥30 in 2006/07 [3]. As a matter of fact obesity isn't only a problem with adults, it is observed as a growing occurrence in young people [4, 5, 6, 7]. In 2006 in Austria there were about 29% of the boys and 42% of the girls, aged 0 – 18, overweight and 11% of the boys actually obese [7]. According to Rieder et al [7], 40% of today's overweight children will still be overweight, when being adult.

According to Statistik Austria data [3] there have been 4.398 deaths caused by alimentation and metabolism diseases in Austria in 2008 of which 3.385 are due to diabetes mellitus type 2, which in return is one of the major consequences of obesity [1, 7, 8, 9].

Mortality isn't the only consequence of the prevalence of obesity. There is a large list of resulting sicknesses, comorbidities and diseases, of which obesity is a huge risk factor [7, 9, 10, 11] shown in Fig. 1 and, as a matter of fact, it is a great cost factor for the health care system and also for every person as direct costs, like actual costs for self afforded medication and slim down programs and indirect costs, like inability to work, unemployment, pain and loss of quality of life [7, 8].

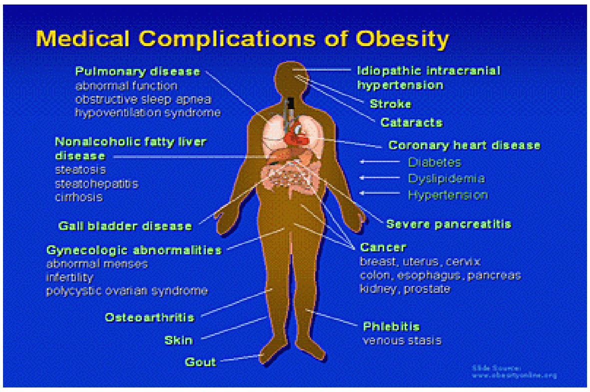

Fig. 1 Medical complications of obesity [12]: The picture shows only some of the comorbidities.

All of those diseases are connected with a huge amount of costs and therefore it is very important to reduce prevalence of obesity.

As mentioned before, obesity is also a worldwide problem, because according to WHO data [2] over 70% of the population of Saudi Arabia are overweight and about 35% are obese and so is the population in the USA and other countries as shown in Fig. 2:

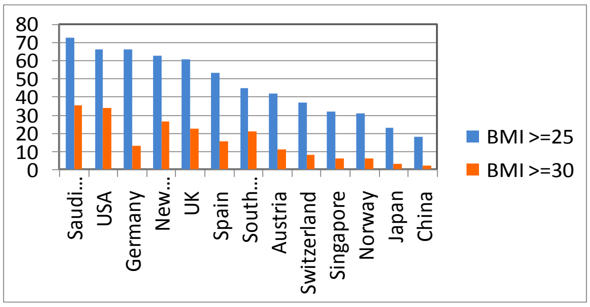

Fig. 2 Overweight and obesity worldwide [2]. Blue bars represent overweight and obese population and orange bars represent the obese population (%).

When thinking about the consequences of a disease, one has to think about how it started first, which means to identify the factors influencing obesity and thus the *caloric balance*, which in most literature is considered to be the direct influencing factor on weight [13, 14]. This is the balance between caloric intake and caloric expenditure.

The human body itself and how biological, social, environmental, physiological and psychological influences act on every person is a very complex and wide ranging system, which makes it an especially challenging problem to understand and study the impact of those influencing factors, and also how possible prevention influences this multi level system.

A general classification of categories is shown in Fig. 3 [15]:

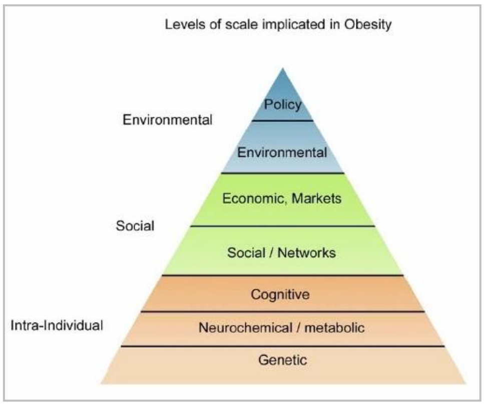

Fig. 3 Influences on Obesity: Three levels of influence on a person, which are influencing the caloric balance. They are further subdivided into more specific categories.

The first level includes the individual factors, like the influence of genes [7]. The next level consists of the social environment [7, 16], like friends, family and also markets. The last level is the environmental [7], like how many possibilities one has to exercise, how many fast food restaurants are in the neighborhood and policy strategies.

After having realized and identified the most important factors, one can start building a model of how those parts interact and react on a human body, the health care system and as a matter of fact on the system itself. So, there is definitely feedback in the whole system, which has to be understood, but which is a very challenging problem, as one can see in the next chapter.

2 Various Modeling Approaches

There have been several modeling approaches in some countries for obesity and the consequences of this disease for the person and also for the health care system. The next few examples of models are not due to a systematic review of the literature, but due to a concrete problem: obesity dynamics, and they are result of a directed search for different modeling approaches: differential equations (chapter 2.1), Markov Modeling (chapter 2.2) and System Dynamics (chapter 2.3).

After a short presentation of the models their advantages and disadvantages will be discussed in chapter 3.

2.1 Differential Equations

Differential equations are widely used in such fields as physics and biology to model the evolution of certain processes that vary over a period of time and allow the introduction of the flow of individuals from one state of health to another, for example the transition of one BMI category to another. The first model for obesity prevalence predicts the incidence of obesity in the 3 – 5 years old population in the coming years in the region of Valencia, Spain and analyzes the possible strategies in order to prevent the spread of obesity [17, 18]. A dynamic system of coupled nonlinear differential equations was introduced and this continuous model is based on a partition of the infant population into six subpopulations as shown in the flow diagram in Fig. 4:

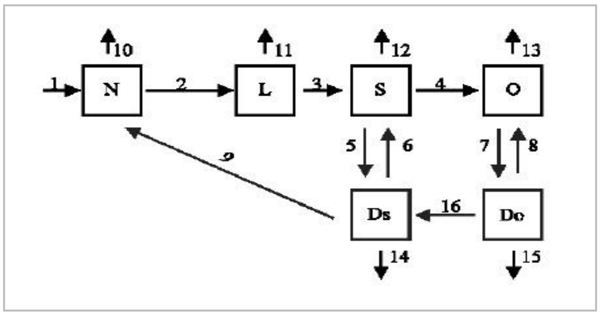

Fig. 4 Flow diagram of the population in the mathematical model [20]. Children transit between the subpopulations N, L, S, O, D_S, D_O according to the labels 1 to 16.

In this model the population is presented by the six levels, each of them dependent on time *t* in weeks. N(t) are those with normal weight, L(t) those with normal weight, but unhealthy eating habits named latent, S(t) those with overweight, O(t) those who are obese, $D_S(t)$ are overweight children on diet and $D_O(t)$ obese children on diet. There are three assumptions considered in the model:

- Overweight and obesity of the observed population is due to BFS (bakery snacks, fried food, and sugared soft drinks)
- Eating habits of the parents determine those of the children, since they are aged 3 – 5.
- A homogeneous mixed population is assumed, meaning all family units have equal probability of interrelation. Furthermore, it is assumed that the social contacts are random and that unhealthy eating habits and thereby obesity is acquired through this contact.

Every compartment represents a differential equation. An inflow represents a positive contribution of the label and an outflow a negative one.

2.2 Markov Model

Markov models are mainly used in medical technical applications [19, 20] to model long-term, progressive diseases, which was the reason for doing a research on them too.

The model introduced here [21] is a non-homogeneous Markov chain that describes the transition of patients, who had adjustable gastric banding, between one absorbing state (death) and four recurrent states, representing the BMI states. The patients enter the model with a BMI greater 40 (hence the additional division of the BMI WHO – classification category shown in Tab. 1 is necessary), because that is the minimum of BMI a patient has to have to get such a surgery. The Markov Model is shown in Fig. 5.

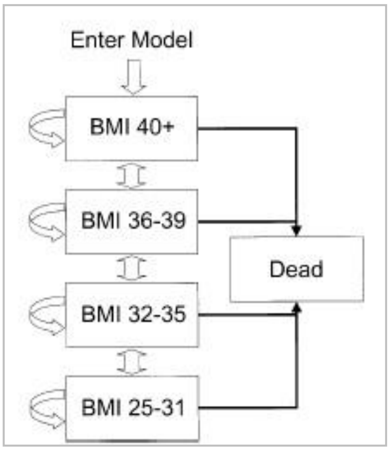

Fig. 5 State Transition diagram of the Markov Model for patients who had adjustable gastric banding to estimate life expectancy in patients with BMI ≥ 40.

In each state the patients are at risk of dying or moving to an adjacent BMI stratum. The scenarios are simulated for each sex and age separately. All patients enter the model through the BMI 40+ level and there were several disease histories taken into account. Furthermore in each scenario, the Markov Model run with the use of Monte Carlo simulation [19]. In each scenario a hypothetical cohort of 10.000 individual patients was followed through the model until everyone was in the absorbing state 'death'.

2.3 System Dynamics Model

System Dynamics is a common used approach to understanding the behavior of complex systems and what makes it different from other approaches to studying complex systems is the use of so called feedback loops and stocks and flows. This methods have been used for nearly fifty years now and started with Jay W. Forrester in 1961 [22].

The model in this subsection that will be discussed is Homer et al. [13]. The simplified model structure is shown in Fig. 6. As one can see the population is divided into compartments depending on age and severity degree of the disease. Every year of age of a person is modeled separately and the severity degree of obesity is divided into 4 categories of BMI. This means that there are 4 x 100 (ages 0 to 99), thus 400 compartments and each one of them has 2 (resp. 3) flows out, because every person is first of all aging, which means a down flow (blue line) in the structure in Fig.6 and every person can change his/her state of BMI, which means a flow down right (red line) when the person is gaining more weight or a flow down left (green line) which means that the person is losing some weight.

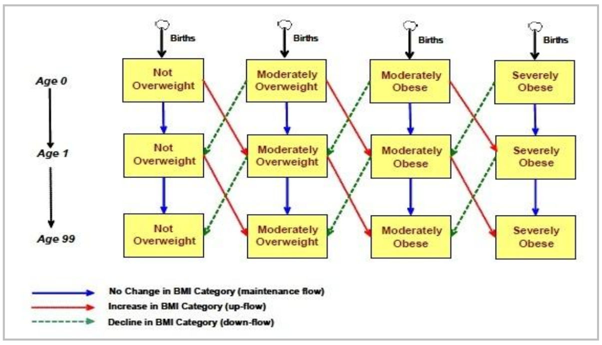

Fig. 6 System Dynamics obesity Model by Jack Homer 2006 Part 1: Population is divided into levels representing states of BMI and ages.

Fig. 7 shows additionally the causes of the flows:

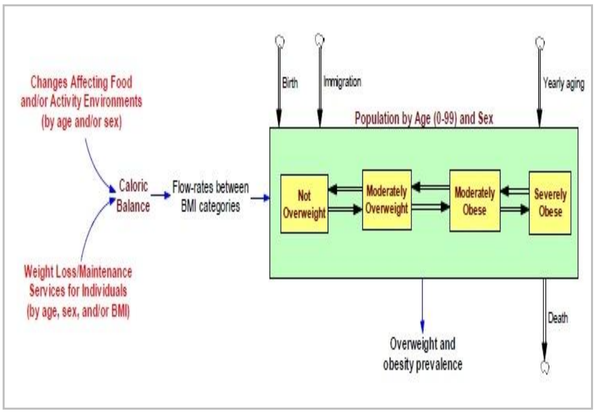

Fig.7 System Dynamics obesity Model by Jack Homer 2006 Part 2: Entering the model through birth, immigration or aging, and exiting it through death. Also taken into account is the caloric balance as flows between the levels.

On the left side of the green box in Fig. 7 is the caloric balance which affects the flows shown in Fig. 6. As a matter of fact every compartment, which means every person with different age and weight, has a different basal metabolic rate [23]. From the modelers point of view this can easily get very confusing when trying to implement such a model, because every compartment has an own flow for caloric balance.

3 Advantages and Disadvantages of the models selected

As one can see, most of the models explained here use homogeneous populations, which in some cases is acceptable, but with the aim of modeling obesity dynamics it is necessary, as stated in chapter 1, to look at the population at different ages, sexes and severity degrees of the disease.

3.1 Advantages

Severity Degrees. Every model for obesity splits the severity of the disease into 3 – 4 levels, which is good, when modeling the spread of obesity, where overweight people are at higher risk for developing obesity than people at normal weight.

Sex. Metabolic rates, for example, are different for men and women [23] and according to some studies [7] the normal body fat fraction for men lies between 20% - 30%, whereas the one for women lies between 10% - 20%, which in return has an applicable influence on the metabolic rate of each person. And so, it is important to split between men and woman, which isn't explicitly done in the models above, because that would mean that one has twice as much numbers of levels in the models in Fig 4, 5, 6, 7. In the System Dynamics study in Fig. 6 and Fig. 7 there were separate runs of the existing model. In the differential equation model (see Fig. 4, chapter 2.1) there is no differentiation, which wasn't considered to be necessary as modeling only 3 – 5 year olds. When trying to adopt this model for other age groups, it will be necessary and only possible by running two simulations, one for men and one for women.

In the Markov model in chapter 2.2 (Fig. 5) there were also two runs, one for men, one for women, and so there was no influence from men to women, or vice versa.

The problem, resulting in running more simulations, than including the men/women differentiation from the beginning will be discussed in chapter 3.2.

Age. Only the System Dynamics model seems to directly include ages of the persons, meaning constructing a level for each age and as a consequence one can see the influences of a large level of young obese persons (represented as a yellow box in Fig. 6 in the upper right part of the model) on older persons with time delay. Once a person is in the obese part, it is more difficult to get into a non obese part. So this model is very good, when looking at persons for a long time. From the modelers point of view there are some disadvantages, which will also be discussed later.

Inhomogeneity. The System Dynamics Model is the only one, which takes directly into account the inhomogeneous population. The other models make a difference just through simulations with other parameters of the existing model and so there can never be a feedback from men to women or one age to another, which in case of obesity is important, because as a matter of fact, and also assumed in the Markov model, parents have a direct influence on their children with their eating habits.

3.2 Disadvantages

As mentioned before, the fact that obesity has so many influencing factors and also so many levels, which have to be looked after (Fig. 3), it is difficult to simulate all those factors in one model. The differential equation model consists of only one age group, the Markov model and also all the others didn't include men and women in one model.

The problem with running different simulations for different dimensions (age, sex) is that they can't influence each other in the model, which they do in reality and additionally one can't simulate a person getting older through time and maybe having some feedback on himself or his environment.

4 Alternative Approaches

Modeling such a complex system with all its components and full particulars is difficult. A satisfying approach has to include at least sex differences, age differences and of course the severity degrees. Furthermore there should be feedback in the model, because the human body as well as the environment with each person consists of feedback, for example see Fig. 8 showing a reinforcing feedback loop. It should be possible to build such a complex model, as shown in the System Dynamics Model in chapter 2.3. There is influence from each age level on itself and the other age levels, on each sex and in every severity degree. When modeling that structure, it will get very soon very confusing, because there are so many stocks and flows.

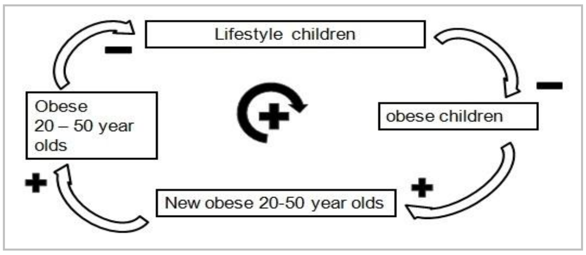

Fig. 8 Reinforcing Feedback loop: The more obese adults, the worse gets the young people's lifestyle and so the more obese children are in the system. Those obese children become, with time delay obese adults.

Another approach is to build an Agent Based Model, with agents being persons or groups of persons or food industry in general [15, 24]. These agents are placed in an environment with specified starting conditions and given a set of adaptive rules for interaction with each other and with their environment. In this case every agent has a sex, age, height and weight (or BMI) and with their decisions they produce output for agents themselves and also for the whole system. The advantages of an Agent Based Model for obesity are diversity among agents, and the fact that no homogeneous pools or other aggregated forms are needed, because every individual is represented. A multiple level of simulation is possible by simulating each person as an agent, and within the agent there might be a representation of metabolic mechanisms or genetics.

5 Conclusion

There are no boundaries of the complex system obesity, meaning there are a lot of influences and also a lot of consequences and details. Agent Based Modeling, thus modeling bottom-up, is appropriate modeling the details, but building a System Dynamics Model is much easier and perspicuous, when modeling the system as a whole. That's the reason why System Dynamics is such a powerful simulation tool when it comes to modeling health care problems [25, 26, 27, 28]. We can't see the detail, which at some point isn't necessary, but we can get a look at the big picture.

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