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Use of System Dynamics Modeling in Medical Education and Research Projects

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Abstract. The paper reviews experiences and accomplishments in application of system dynamics modeling in education, training and research projects at the Andrija Stampar School of Public Health, a branch of the Zagreb University School of Medicine, Croatia. A number of simulation models developed over the past 40 years are briefly described with regard to real problems concerned, objectives and modeling methods and techniques used. Many of them have been developed as the individual students' projects as a part of their graduation, MSc or PhD theses and subsequently published in journals or conference proceedings. Some of them were later used in teaching and simulation training. System dynamics modeling proved to be not only powerful method for research and decision making but also a useful tool in medical and nursing education enabling better understanding of dynamic systems' behavior.

Keywords. Computer simulation, Decision Support Techniques, Modeling and simulation, Simulation Training, System Dynamics

Introduction

Two main types of simulation models are discrete event simulation (DES) and system dynamics (SD). DES is aimed for detailed description of system behavior modeled as a sequence of discrete events or system's state changes at specific points in time with use of stochastic variables. SD aggregates entities and events in stocks and continuous flows in order to simulate the behavior of complex systems which are supposed to be deterministic in nature although they include variables (flows or rates) of probabilistic character [1-4]. Although there are a number of similarities between the two methods in regard to basic concepts, objectives, steps in a sound simulation study, application domains and analysis of simulation results, simulation software for respective applications is based on different techniques [1-4]. Both methods are used in many very diverse areas including biomedical research, epidemiology, public health and health system research [4]. Their use in education has a long tradition, too [5]. In order to simulate real world phenomenon with a set of mathematical formulas one can develop special program written in virtually any general-purpose programming language (or even use a tool like spreadsheet program) or exploit one of the application-oriented simulation packages [1,6-8].

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The principles of SD were originated during late 1950-ties at Massachusetts Institute of Technology (MIT). Professor Jay Wright Forrester did a lot of work on modeling of all aspects of industrial systems and urban growth and published a series of books and papers covering methodological fundamentals and including informative model examples during 1960s and early 1970s (not cited here).

The work on SD principles was supported and went along with development of simulation programing languages. DYNAMO (DYNAmic MOdels) was the first one developed at MIT and released firstly for mainframes and in early 1990-ties also for microcomputers [9,10]. STELLA/iTthink software has been developed in 1984 by Barry Richmond, former Prof. Forrester's graduate student as iThink for the new Macintosh computers, followed by STELLA for Windows (produced by High Performance Systems later renamed in ISEE systems) [11]. Those SD software packages have been designed with intention to promote modeling and simulation activities and aimed as a tool for system thinking, a disciplined way for better understanding of dynamic relationships and supportive tool for decision making and policy informing. They include tools facilitating model implementation and validation (graphic user interface for model implementation, graphic presentation of simulation results including animation) and have become widely used in very different domains. Important advantage was systematic approach and availability of well written manuals and comprehensive guidebook firstly published in 1992 [11]. Other similar software products became available commercially or for free (e.g. PowerSim and Vensim PLE). Majority of them enable "step-by-step" approach that integrates validation with model developing process and establishment of Windows based environments for modeling and simulation with many advanced functions (e.g. the option enabling packaging of developed model for distribution in a form of interactive game or medium functional for learning/training about real world phenomena in an accurate, realistic, safe and secure system thinking learning environment.

SD proved to be applicable to very different real problems including those concerned with processes in a human body or population. Instead with accumulated row material or produced goods in stocks (levels or reservoirs), such models deal with the amount of drugs, enzymes or nutrients in a particular tissue (e.g. bloodstream) or virtual aggregation of units (e.g. molecules, cells, animals or people) in a certain state regarding the disease under consideration. The aim of this paper is to present experience in use of SD modeling applications in education and research projects at a higher education institution in Croatia and to review developed models regarding the real problems involved and modeling design, methods and software used.

1. Experience in the Use of SD Modeling in Medical Education and Research

Simulation modeling methods with emphasis on SD have been taught to medical and graduate students at the Andrija Stampar School of Public Health (AS-SPH) for almost 40 years within courses in Medical Informatics, Epidemiology, Public Health and Research Methods in Public Health and Healthcare [12]. System thinking and modeling approach proved to be useful aid enabling better understanding of dynamic systems behavior and powerful tool in research including students' and graduates' projects that were part of their graduation theses.

Modeling of spread of infectious diseases in population started at AS-SPH in the late 1970-ties initiated and steered by Professor Branko Cvjetanovic (1918-2002) as a continuation of his work in the World Health Organization Headquarters in Geneva where he used to be chief medical officer in the Department of bacterial diseases till his retirement in 1978 and leader of a team developing SD epidemiological models [13]. Mathematical theory of infectious diseases' dynamics has been already well established at the time [14]. In multi-compartmental models human population is represented as a set of compartments containing people in a certain state regarding the disease under consideration (e.g. susceptible, sick, resistant, carriers) with flows between them.

The model of shigellosis was the first one developed by our group in late 1970s and followed by models of other diarrheal diseases [15-18]. Shigellosis model was further advanced by introduction of sensitivity analysis to its parameters' changes. The models of whooping-cough and typhoid fever were based on earlier designed models' structures with revisions introduced with the aim to use them for evaluation of different disease control strategies [13]. The model of whooping-cough dynamics was the first one with age-structured population. Simulation experiments were performed using population data estimated from vital statistics and with different assumptions regarding immunization coverage. It was shown that the introduction of age-structured population was of crucial importance. In addition to age-structured population, time delays were introduced in rubella and hepatitis A models [19,20]. These models were aimed for the assessment of immunization strategies, namely introduction of immunization programs and their evaluation including cost-benefit analysis.

Population dynamics models of non-communicable diseases were made with the aim to envisage efficiency of different healthcare control programs and interventions for hypertension, schizophrenia and diabetes [21].

A very detailed population structure according to gender, age, genotype and phenotype was implemented in a research project aimed for validation of population control strategy of phenylketonuria, recessively inherited genetic disease affecting individuals if they are not diagnosed and treated with appropriate diet timely after birth. There were altogether 128 compartments in phenylketonuria model structured for two genders, 16 age groups and four classes of genotype and diagnosis/treatment status (healthy homozygous, heterozygous, sick not timely treated and sick timely treated). Age-specific fertility rates were estimated from vital statistics and enabled calculation of number of newborns entering the youngest compartments according to estimated phenylketonuria gene frequency in population. Secondary use of this model enabled demographic projections of Croatian population.

Mathematical modeling and SD has been employed in modeling of cancer incidence in population in order to enable better understanding and interpretation of cancer incidence trends in different populations (e.g. colorectal and testicular cancer) [22-24]. Epidemiological data reported by cancer registries as well as experimental data acquired from experimental studies were used in modeling of cancer incidence, formation of melanocytic nevi during life course, cerebral cortex neurogenesis and other cellular and/or histological growth processes and spread of diseases in population [22-26].

Simulation modeling approach was also employed in an operational research project undertaken in 1989 for estimation of future needs and supply of health personnel in Croatia. The project was initiated due to surplus and high unemployment rate of medical doctors in order to enable decision making and informed policy for enrolment into medical and nursing programs at national level. The actual numbers of health professionals (MDs, nurses, medical technicians) in 5-year age groups were taken as initial values. Simulation experiments were performed with different assumptions about number of enrolled students and other relevant variables. It was just one year before we turned from 5-year to 6-year medical curriculum. A decrease of enrollment quotas to medical schools based on our recommendations took place in 1993 [27,28]. Twenty years later we reconsidered and revised model and used it again in changed circumstances when a lack of medical doctors became evident and shortage of health personnel further deteriorated after Croatia's accession to EU in 2013. It was necessary to further develop the model by inclusion of additional elements (e.g. those influencing push and pull factors). The model for planning of medical doctors' specialist training is under development as a part of a research project for PhD thesis already presented in Doctoral Colloquium at Medical Informatics Europe 2016 [29]. Currently it is a very hot topic seeking informed decision making due to increased migration of specialist to other EU countries and claims for centralized and better planned specialist training as well as the possibility of changes in immigration policy.

2. Discussion

More than 20 simulation models have been developed at our institution within research projects or as a part of graduation theses (Master, MSc or PhD). Many of them were published in scientific journals and conference proceedings and further used as instructive examples in undergraduate, graduate and continuing education. Selected list of references is included in the present paper while a complete list of students' and graduates' research projects and graduate theses could be found elsewhere [12]. Introduction of simulation modeling as a topic in higher education curricula was accompanied by preparation of textbooks and manuals written in Croatian [2,30].

In late 1970s and beginning of 1980s we used UNIVAC 1100/42 mainframe computer at University Computing Centre in Zagreb and simulation programs were written in FORTRAN and capable of giving results in numerical and graphical form [15-18]. The appearance of personal computers in 1980s offered new possibilities enabling flexible development and use of spreadsheet programs for DES and SD simulation models [6-8]. Despite the fact that commercial products for simulation modeling were at market already in 1970-ties, they were not always affordable to us and that is why we had to develop original tools and software solutions [6].

Collaboration was established with colleagues dealing with simulation modeling at other departments/schools of the University of Zagreb as well as within the Croatian Society for Simulation Modelling (CROSSIM) and the Federation of European Simulation Societies (EUROSIM).

3. Conclusion

Simulation modeling has been used in many very diverse areas including biomedical research, physiology, epidemiology, public health and healthcare systems research. System dynamics proved to be powerful method not only when used in research but also as a tool in decision making providing necessary information to policy makers. System thinking approach should be further promoted. Simulation modeling might be included in medical curriculum provided that in higher education it could come to its full potential not only as research and decision making tool but also as a teaching tool assisting students in better understanding of dynamic systems' behavior.

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