discrete event simulation, modelling, healthcare, regional system

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ADVANCED SIMULATION MODELS OF REGIONAL HEALTHCARE SYSTEMS

We discuss further contributions to the problem of creating a simulation model of a complex regional healthcare system and implementing it using real-world data. The approach is based on modelling patients' pathways comprising diagnostic and treatment processes throughout patients' stay in the system. The general structure of the model and two main modules are outlined, with observations on problems regarding modelling logical processes within the regional system, and pitfalls when modelling large real-world systems. We illustrate the approach with a sample model of a regional system of hospital care in the Lower Silesia Region of Poland for lung cancer patients.

1. INTRODUCTION

Simulation modelling has been for years used to support solving complex decision problems in healthcare systems. In many cases the subjects of modelling are specific healthcare units, such as hospital wards, operation theatres, emergency departments, or ambulatory clinics. One of the most frequent modelling approaches in the field is based on queuing-system or patient-flow perspective, where specific healthcare resources are used for serving streams of patients sequentially travelling through the units of the system. A specific, patient-oriented framework of this type is based on Clinical Pathways, also called Pathways of Care or Clinical Profiles [7], which model the 'path' followed by an ill person through a healthcare unit or clinical process. The path may be defined for single 'episodes' of care (e.g. thyroid surgical treatment, performed at ambulatory and hospital level, from initial endocrinologist consultation to hospital-based surgery and follow up [8]), or for multiple 'episodes' of care, constituting a multi-level long-standing sequence of diagnosis-treatment-follow-up episodes (e.g. for lung cancer (LC) patients, undergoing multiple procedures in a number of

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healthcare premises [6]). In the latter case, single ‘episodes of care’ (e.g. radical surgery plus a series of chemotherapy or radiotherapy) can be standardized and modelled in the same way as for the first case, but the repetitions of the ‘episodes’ are difficult for modelling, as they greatly depend on primary disease progression, co-morbidities, physical and mental condition.

In addition to patient-centred perspective, when deciding on the best use of available resources, medical technologies and selecting the most efficient clinical pathway (best care for an individual patient), healthcare decision makers look at the same problem from system-wide perspective, deciding on the use of scarce resources of healthcare systems for the benefit of a population of patients (greatest good for greatest number). Some well known examples of modelling projects of this type include models for specific care groups (emergency care [2], coronary care [1,3], or thyroid surgery[8]), or investigations of specific formal problems arising when modelling complex healthcare systems (designing simulation experiments to evaluate surgical care policies [9], or comparing conventional and distributed approaches to simulation of complex health systems [5]).

The present authors extend previous results [6] in developing a simulation model of a complex Regional Healthcare System (RHS) and discuss problems associated with implementing the model using real-world data from a regional system of hospital care in the Lower Silesia Region of Poland. To simplify the presentation, the considerations are limited to the category of thoracic surgery (TS) and pulmonary oncology LC patients. The ultimate goal of developing the model is to provide an Intelligent Decision Support Environment, which could assist regional healthcare management decisions, using patient-centred (patient pathways based) and system-wide perspectives.

The paper is organized as follows. In section 2 we outline the assumptions and general structure of the model. In sections 3 and 4 we present selected logical processes associated with two main modules of the simulation model: First_arrivals and First_hospital_stay. In section 5 we discuss specific issues of implementing the model with ExtendSim [4] and conclude on the actual results of the model development.

2. MODEL ASSUMPTIONS AND GENERAL STRUCTURE

The simulation model described here is a generalized version of a first prototype presented in [6]. It was developed using discrete-event-simulation methodology to investigate processes in a regional healthcare system of hospital care, serving population of a number of districts. Due to the specificity of the selected category of patients (hospitalised surgical LC patients), it is assumed that the patients, once in the system, may expect multiple ‘episodes’ of care, each consisting of the first diagnostic hospital stay and a number of consecutive stays of specific type (e.g. surgery followed by chemotherapy), while particular stays may take place in different hospitals. Taking into account patient-centred perspective, the following main modules of the model could be defined:

– module 1: First_arrivals of the new-comers to the hospital care subsystem,

– module 2: First_hospital_stay, when main and subsidiary diagnoses are specified, and treatment pathway (methods and sequences) is defined; this module is further decomposed into:

– submodule 21: an interface between arrivals and admission to hospital,

– submodule 22: A&D/ED (emergency department), where decisions on patient admission or transfer to another hospital are made (on the basis of patient status as well as available resources: beds, financial limits),

– submodule 23: Hospital_Wards, modelling diagnostics and initial treatment,

– module 3: First_pathway, consisting of all hospital stays defined by the treatment pathway except the first (diagnostic) hospitalization,

– module 4: Next_pathways, which include: return to district when the first pathway is finished, and consecutive 'next_arrivals' and 'further_pathways', as needed according to patient status (e.g. reoccurrence or co-morbidities).

In addition, taking into account the regional healthcare perspective, we could define functional modules, which interfere with all patient-centred modules:

– population demography and epidemiology module (which determines parameters of the main first arrival and subsequent arrivals processes),

– healthcare resources module (hospital network, wards, beds, budgets, etc.),

– regional healthcare finance module (which in particular determines available hospital budgets and allocation or payment procedures),

– public health and policy module (e.g. health threats, inequalities in access).

3. MODELLING INPUT PROCESSES (FIRST_ARRIVAL)

Each would-be patient enters the system according to a dynamic random Poisson process with time-varying and district-dependent parameters (equal the reverses of the values for each district and particular date, as presented on Fig. 1); inter-arrival times are defined for particular year, day of the week, district of residence, and are recalculated as frequencies for each day of the simulation period. The resulting hierarchical model, as implemented in ExtendSim, is presented on Fig. 2.

Enter a schedule of arrival times

DB	_Create Time	Value	Value	Value 3	Value 4	Value 5	Value 6	
1	1/1/2006 0:00	1	2006	0,0112179487179	0,0080128205128	0,005608974359	0,0040064102564	0,0[illegible]
2	2/1/2006 0:00	2	2006	0,0495283018868	0,0448113207547	0,0369496855346	0,0149371069182	0,0[illegible]
3	3/1/2006 0:00	3	2006	0,0328525641026	0,0528846153846	0,0328525641026	0,0120192307692	0,0[illegible]
4	4/1/2006 0:00	4	2006	0,0344551282051	0,0536858974359	0,0264423076923	0,0088141025641	0,0[illegible]

Fig. 1. Schedule of inter-arrival times distribution (Create Block) for specific districts

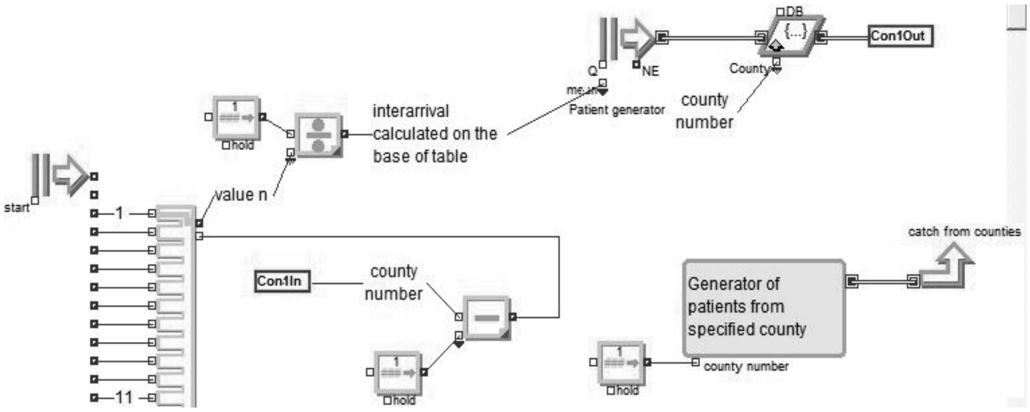

Fig. 2. Hierarchical block (lower right) and its structure for stream of patients from a district

Having generated an object from a particular district (a newcomer to the system on a particular day), the attributes of the object, namely: gender, age group, main disease (ICD-10 group), clinical priority (standard, urgent or critically ill), and number of hospital for the first admission, are determined, using input data database (Fig. 3), and dynamic procedures of selecting and using multi-attribute frequency distributions. The sample source input data, presented on Fig. 4-5, have been determined in a Data Mining project [6], which comprised analyses of the relationships between specific attributes, using Feature Selection and Variable Screening module of Statsoft STATISTICA 10 software (in the case study there are 29 districts, 36 hospitals with over 15k beds, serving approx. 5.5k newcomers per year, for the first time admitted to a hospital).

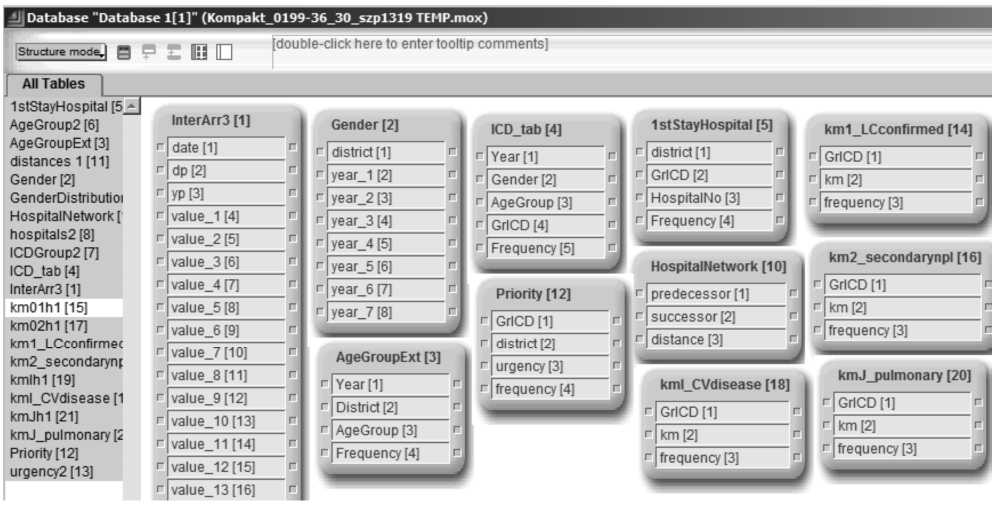

Fig. 3. Structure of the main model database, indicating assumed inter-attribute correlations

(a)

DB	Year	Gender	Age_Group	ICD_Group	Probability
152	2006	0	2	49	0,02247191
153	2006	0	2	50	0,16853933
154	2006	0	2	51	0.
155	2006	0	2	52	0

DB	County_number	ICD_Group	Hospital_Number	Probability
53384	29	27	33	0,120689655
53385	29	27	34	0,103448276
53386	29	27	35	0,465517241
53387	29	27	36	0,034482759

```
(b) real data;
Year = EDDateValue(EDGetCurrentDate(),9);
data=DBDataGetAsNumber(1,2,Year-2004,county);
DBDataSetAsNumber(1,9,2,1,data);
DBDataSetAsNumber(1,9,2,2,1-data);
(c) real Year, data;
integer auxiliary, i;
Year = EDDateValue(EDGetCurrentDate(),9);
auxiliary=(Year-2006)*29*10+county;
for (i = 0; i <10; i++)
{ data=DBDataGetAsNumber(1,3,4,auxiliary+29*i);
DBDataSetAsNumber(1,6,2,i+1,data); }
```

Fig. 4. Sample parts of multivariable empirical distributions (a) as well as ModL language code for database update enabling dynamic generation of gender (b) and age group (c)

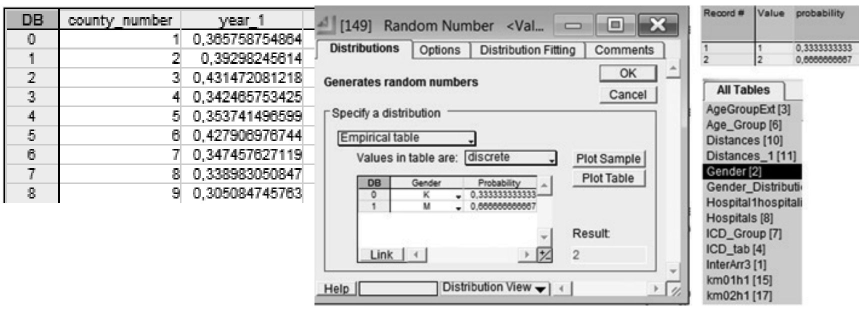

Fig. 5. Linking Table Gender from Database to Empirical Table in Random Number

4. MODELLING INITIAL PATHWAY (A&D AND FIRST HOSPITAL STAY)

The first phase in the initial pathway (submodule 21) is concerned with creating specific object admission attitudes for ordinary (elective) versus urgent and critical (emergency) patients, having been generated in the previous 24 hours of simulation time. It is assumed that emergency patients once generated are sent to the selected hospital, while elective patients have determined time-slots each day (e.g. admission hours 8–12 am). Patients of the latter class should wait until the time-slot, so in the model they must be grouped in a buffer (Fig. 6), which can be described as bunching phase. Technical implementation in ExtendSim involves creating a virtual activity block (lower right on Fig.6), which processes a virtual object generated at the start of the time-slot and activates gate opening signal for Select_item block, which in turn enables all waiting objects to enter the A&D processing buffer.

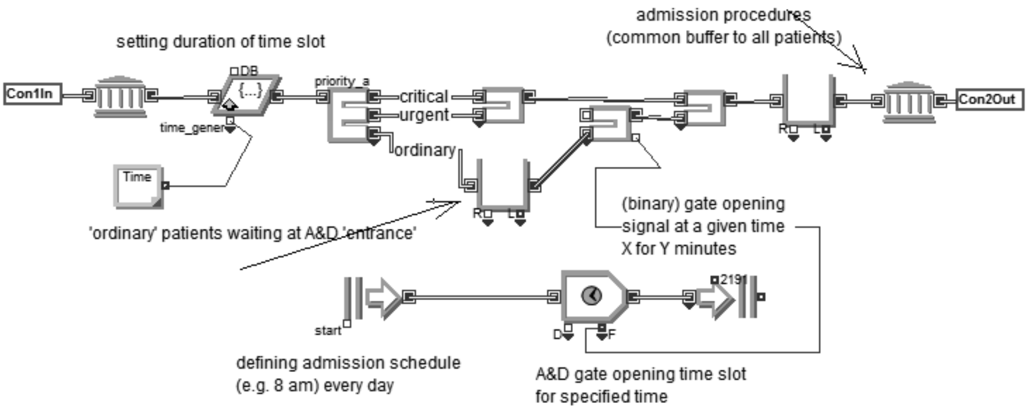

Fig. 6. A simplified diagram for bunching phase (grouping standard patients, waiting for admission hours in a particular hospital)

The most complicated submodule in the current version of the model - sub-module 22 (A&E/ED department at a particular hospital) - is used for making admission decisions for mixed priority newcomers, as well as objects transferred from other hospitals (due to lack of empty beds or monthly limit overspending), and objects assigned to the hospital, coming for subsequent care episodes of their current pathway. Decisions are made in relation to particular categories of resources, and - on the basis of a set of decision rules, each of which sets off a series of calculations or activities. For instance a simplified general rule for urgent (not critical) newcomers may be formulated as:

if an emergency_bed free then assign_scl (subject to cost limit) else if a standard_bed free then assign_scl else if standard extra_bed available then assign_scl else if a standard_bed is to be vacated within h hours then assign_scl else look for an empty bed in other hospitals else assign a (virtual) unlimited bed with immediate preemption, i.e. transfer to a standard bed once it is vacated.

Once the decision rule is fired, it involves starting a number of activities, for instance checking current balance for the hospital (assign_scl) or determining the earliest completion dates for ward service in this or the nearest hospital. Fig. 7 illustrates connection between the A&D (22) and Hospital_wards (23) sub-modules. The latter one models medical procedures for patients admitted to a hospital, using assumptions concerning statistical features of processing times (LOS - length of stay in a hospital) and costs, modelled using results of statistical analysis of the real-world data [6]. In the case study the following assumptions have been made:

– results of diagnostic phase are defined as clinical attributes, depending mainly on the main diagnosis (frequency distributions of attributes km; Fig.1), and generated simultaneously using a dedicated model unit (Fig. 8),

– output distributions for length of stay and costs are fitted as theoretical distributions separately for each combination of priority and all four clinical km attributes; for instance for patients with confirmed LC with metastases, as well as pulmonary and cardiac complications, the LOS is fitted as Lognormal with parameters minimum, mu, sigma equal (0.329, 2.04, 1.15) respectively.

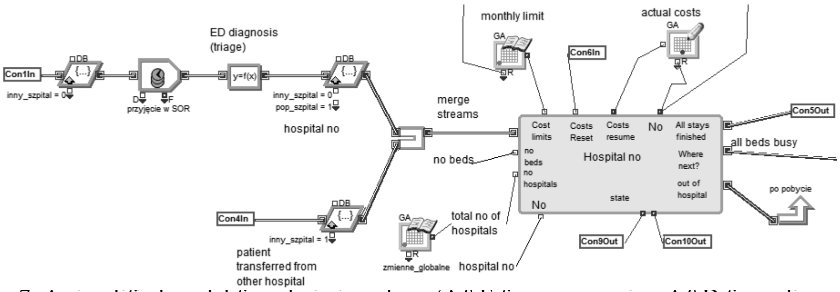

Fig. 7. A simplified model for admission phase (A&E for emergencies, A&D for ordinary)

```
(a) real given_probability;
integer i; auxiliary=ICD_Group;
//km01h1
given_probability=DBDataGetAsNumber(1,14,3,auxiliary);
DBDataSetAsNumber(1,15,2,1,given_probability);
DBDataSetAsNumber(1,15,2,2,1-given_probability);
```

(b)

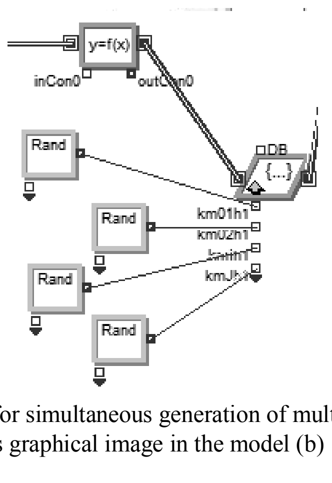

Fig. 8. Sample ModL language code for simultaneous generation of multiple hospital stay attributes (a) and its graphical image in the model (b)

As described above decisions in the A&E module for consecutive objects are made in accordance with the state of the Hospital_wards module with the objects admitted so far. Fig. 9 presents a simplified model of pre-empting (PE) ward service of patients assigned to unlimited extra beds. In this case Activity blocks with PE option have been used, where PE function is initiated according to the priority of the object, using current dynamic information on beds (of different type) in use and current status of the objects on unlimited extra beds; the remaining process time is stored in an attribute and used for completing the service on standard beds once available.

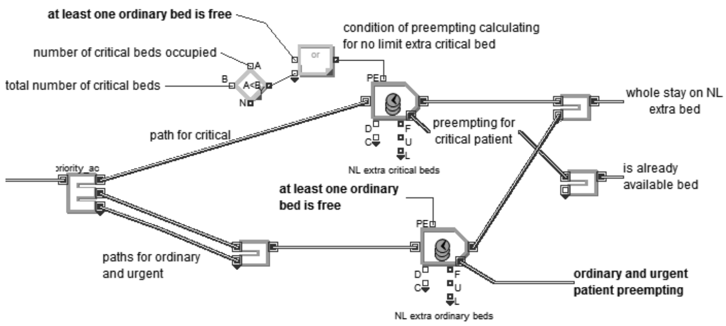

Fig. 9. Sample model of pre-emption unit for unlimited extra beds

5. TECHNICAL IMPLEMENTATION ISSUES AND CONCLUSIONS

The model was implemented in ExtendSim AT 8.0.2 [4], which proved to be a flexible discrete event simulation environment. Nevertheless a number of technical problems had to be solved in this project stage. For a large number of recognizable objects (approx. 150k newcomers and over 0.5 million stays for standard parameters and 5-years simulation period) and realistic simulation parameters required for statistical accuracy (50–100 runs have been used), both the memory considerations and the speed of simulation resulted in designing problem-oriented input and output data management solutions. In particular to enable validation and further statistical analysis of the output data the following solution for output data collection from a large number of runs (15 million of objects, each described with 10 attributes) was developed (Fig. 10)

– determine the number of global objects (that is incremented in subsequent runs) and save the number of objects of the next iteration in a separate, dedicated global array,

– allocate a global array needed to store the attributes of objects (to take care of saving the working memory)

– read the attribute set of the objects and save them to the resulting global array,

– export filled global array to a text (csv) file at the end of all runs.

```
(a) integer arrayIndex, arrayIndex2;
integer i,k;
integer j;
arrayIndex = GAGetIndex("l_w");
GAMultisim(arrayIndex, 1);
j=CurrentSim;
if (j==0)
{ GASetInteger(object_number, arrayIndex, j, 0);
 if (object_number==1)
 { arrayIndex2 = GAGetIndex("wyniki_02");
 GAResizeByIndex(arrayIndex2,0);
 GAResizeByIndex(arrayIndex2,inCon0); }}
else
 {k=GAGetInteger(arrayIndex,j-1,0);
 GASetInteger(object_number+k, arrayIndex, j,0 ); }
```

(b)

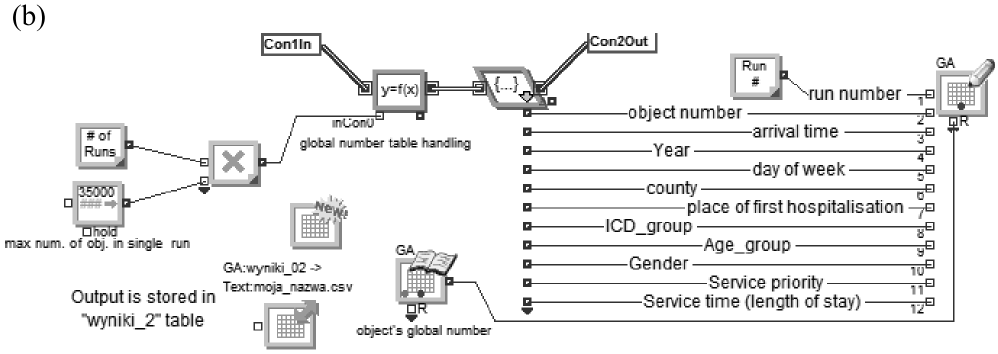

Fig. 10. Sample ModL language code for collecting results of multiple runs (a) and the structure of the corresponding unit of the model (b)

There are also other challenging problems faced during implementation, such as: algorithms for indicating bed vacancies in other hospitals or determining expected times of vacating beds suitable for object of particular priority, dynamic control of monthly limits for particular hospitals and for the whole region. One of the most difficult modelling problems was also selecting the approach for categorizing (data mining phase), defining and implementing conceptual models for region-wide patient pathways (modules 3 and 4).

We conclude with a general observation that in contrast with system dynamic approach, more often applied for modelling large healthcare systems, the application of the discrete-event-based approach enables the modeller to investigate in more details parallel clinical and managerial processes in a regional healthcare system, taking into account stochastic nature of the processes and a great variety of patient categories, resource types and what is very important: detailed costing and payment procedures.

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