Generalized Nets in Medicine: An Example of Telemedicine for People with Diabetes

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Abstract In the present paper, an overview of the Generalized Nets (GNs) models in medicine and telecare/telehealth is given. The apparatus of GNs has been used in the modelling of physiological processes, diagnostics of diseases, organisational and administrative processes in hospitals. Recently, in a series of papers, GNs have been used to model telecare/telehealth services. On the basis of these models, a GN model of telemedicine for patients with diabetes is proposed. The sensors included in the model are blood pressure monitor, weight scale, pulse oximeter and blood glucose monitor. Smart filtering of false positive alarm messages is included which reduces the number of events for which the health care person has to take a decision. The GN model can be used to develop a decision support tool for telemedicine for people with diabetes.

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1 Introduction

Generalized Nets (GNs) are powerful tool for Discrete Event Simulation (DES) and parallel processes flow representation. For the formal definition of GN see the Appendix. The apparatus of GNs is equally well suited for modelling simple systems and for modelling large, complex systems. DES is a method used to model real world systems able to be decomposed into a set of logically separate processes autonomously progressing through time. A major strength of discrete event simulation is its ability to model random events and to predict the effects of the complex interactions between these events. GN-models could be used as a quick method of analyzing and solving complex problems. This reduces the risk and uncertainty associated with important decision making, and increases confidence by supporting the decision with forecasted data. Up to now generalized nets are applied to healthcare delivery systems, general and internal medicine. Many GN models were built which represent various types of organizational and patient workflows, diseases, symptoms and treatments, organs or states of human body. This is possible due to the existence of a proof that every dynamical system and every collection of dynamical systems can be described by a GN (see [7]). GNs have been used as a modelling tool in expert systems and artificial intelligence; computer science; economics, industry and transport; medicine (see [1, 6, 17, 28, 80–82]).

As it is shown in [8, 29, 86, 101, 102, 113] the GN-models in medicine can be used for:

- simulation of real processes with educational aims;
- control of the corresponding hospital processes in real time;
- prognosis of the actual processes in hospital for the purposes of the hospital administration. These models can also help:
- specialists in studying the logic of the processes related to diagnoses;
- medical students and new specialists in acquiring knowledge and diagnostic skills;
- lecturers in medical students examinations with real-time simulations;
- administrative personnel in taking decisions related with planning, management, organization and allocation of the available resources (materials, specialized apparatuses, personnel) and scheduling of the medical specialists.

Up to now, processes in medicine in several directions are modelled with the apparatus of GNs.

2 Modelling of Physiological Processes

Living organisms are featured by a variety of processes flowing in parallel. Some of them, taken separately, are already described by specific mathematical tools, mostly by means of systems theory. These mathematical tools however do not reflect adequately the parallel flow of the processes. In [86], for example, are considered some parallel endocrine processes. These processes are related with production of insulin by the pancreas, introduction of artificial insulin, processing of both types of insulin in the organism, as well as with possible new conditions of production of insulin by the pancreas.

Some other models of physiological processes are presented in [11, 31, 37–39, 41, 52, 71, 72, 80–84, 95–97, 114, 116–118, 123, 124, 127, 134].

3 GN Interpretations of Informational Models of Diseases and Human Body Systems

Modern ideas in every new science with new principles and laws manifestly modify the medical science as well. The attempt to peace together medical informatics and clinical medicine meets some difficulties but as a whole has a lot of benefits.

As it is written in [94] the category "information" in medicine is used for the description of the activities of sensory organs, in genetics, and partly in physiology, pathophysiology and biochemistry. It is found rarely in endocrinology, neurology and psychiatry (where there is a notion of informational disease, illustrating a neurosis due to sensory overloading). In clinical works, the information exchange of the organism is of a very narrow practical significance. Usually, the description of diseases contains morphological changes, dysfunction, etiopathogenesis, metabolism and energy exchange, and relation of symptoms. The fundamental medical sciences seem to support such an approach. The development of GN interpretations of informational model brings medical informatics closer to clinical disciplines and hence raises their effectiveness.

The informational model of diseases proposed by Ivan Dimitrov [52] is based on the following:

1. Cells and organs of the living organism represent a common mechanism, in which they function jointly and in mutual coordination. To achieve this, the elements of the organism communicate, i.e.; exchange of information is carried out among them.
2. In disease, the exchange of information is modified.
3. In the description of diseases, along with metabolism and the exchange of energy, the exchange of information should be included as well.

The development of such an informational model could bring medical informatics closer to clinical disciplines and hence raise their effectiveness. On the other hand, this could enable clinical medicine to improve its models, and perhaps the treatment and prevention of diseases. Undoubtedly, diagnostics can be supported in a decisive way through a profound investigation of information exchange disorders in an organism. The generalized net interpretations of these models are shown in [94]. The basic systems of the human body are:

- Central neurological system;
- Cardiovascular system;
- Respiratory system;
- Gastrointestinal system;
- Endocrine system;
- Hematopoetic system;
- Musculoskeletal system;
- Renal and urological system;
- Reproductive system.

When building a GN model of the human body (see [32]) each of the listed systems can be represented by a transition. These transitions have the simplest form: one input, one output and one input-output place. The last one depicts the interior processes of the respective organ/ system, and contains a token which will have as a current characteristic the status of the corresponding organ/ system.

For completeness of the model input and output places which represent separate organs related to the inputs and outputs of the human body (derma, nose, mouth and tongue, eyes, ears) are added. The tokens which correspond to the exterior factors move through the net and have as characteristics type of the effect and its parameters (power, continuity, volume, etc.).

4 Diagnostics of Diseases

So far GN models are built for diagnostics in nephrology and adult and child neurology. The GN-models in neurology use as a basis some previously made models [53, 138] of the processes in this area.

Decision graphs for diagnostics of isolated (136 in total) neurological diseases are described in [138]. As a whole, the charts in [138] have the form of binary graphs—an initial node (representing the arrival of a patient with a neurological symptom) with two successors representing the alternatives (the patient has/does not have a given symptom). Each arc leads to another node again giving rise to successors corresponding to the presence or absence of symptoms, etc. The graphs make it possible to trace the individual steps of each of these processes. These charts can be used for training of students or professionals. In this sense, the role of the graphs is similar to that of expert systems in subject-oriented areas of medicine [24].

The so made models are used as a basis for construction of GN models, describing the diagnostic processes in adult and child neurology [10, 12–20, 34–36, 44–51, 64–66, 120–122, 125].

At the beginning of the medical diagnostic reasoning or decision making process the practitioner must recognize if a sign or a symptom is significant. As a first step, a detailed patients personal and family history, and complete physical examination are of paramount importance, both in determining their medical significance and in directing evaluation.

Next, the physician begins to sort the data, keeping some pieces of information and ignoring others. The practitioner must first cluster or link some or all of the collected signs and symptoms, and determine any emerging patterns, meaningful groups, and formulate hypotheses. This phase is often referred to as hypothesis formulation (initial, preliminary diagnosis). The formulation of hypotheses or tentative conclusions helps focus further data collection efforts on a manageable group of possibilities.

During the next stage of diagnostic reasoning, the physician focuses on gathering data (laboratory tests, X-ray pictures, and so on) to support or reject the previously generated hypotheses. Once the physician is satisfied that all reasonable explanations for the initial set of signs and symptoms have been thoroughly investigated, each hypothesis must be evaluated in the light of the new evidence that has been collected and a final diagnosis or conclusion reached.

Depending on the course of the final phase of decision making the practitioner determines which explanation has the most supporting data and chooses this hypothesis as the diagnosis. In some cases, however, the clinician can only eliminate hypotheses until only the one with the highest probability remains. A global GN-model for the purpose of diagnosing a definite disease entity is fully described in [17].

Using binary graphs for medical information representation has some advantages. This form of description is very easy for understanding and close to the medical specialists thinking. GNs offer convenience when the specialist's answer is not definitely "yes" or "no". They adequately represent the parallel flow of the processes. In this sense GN-models give possibility for simultaneously examination of several decision paths. This leads to minimization of the times for examinations and decision making. The tokens collect and store in their characteristics all the data that is related to the corresponding examination or patient status. In every moment the whole necessary information is stored in the generalized net and in case of need could easily be obtained. Other models of diseases diagnostic are presented in [21–23, 25–27, 33, 43, 56–62, 64–66, 74–79, 85, 87–90, 92, 93, 98, 103–112, 119, 126, 135, 136].

5 Organisational and Administrative Processes in Hospital Institutions

Modelling such processes with GN offers:

- understanding of the patient flow;
- optimization of the duration of stay of patients in hospital institutions in order to avoid bad-blockage and queuing;
- planning/reassigning of the tasks and activities of medical staff (especially during emergency events epidemics, disasters etc.);
- tracing and monitoring of the treatment of each patient, his/her redirection to another hospital institution;
- detecting bottlenecks in the workflow of the health care structure;
- help in resource planning and allocation, etc.

Medicine is a profession concerned with preserving and improving patients lives. The considerations are thus obvious: the approach has to be patient—centred, and not merely for the convenience of the healthcare providers or administrators. In general, it is difficult to deny the benefits of a more efficient information management system. However, at a less macroscopic level, such generic benefits cannot be assumed for all healthcare delivery systems. Confounding factors such as technical competency of staff, acceptance and adoption by doctors and patients, and intrinsic design—related features can impair rather than facilitate medical care and doctor—patient relationship in some settings.

The automated planning of the resources (necessary equipment and specialists), medical staff working schedules, patients' reception, vastly facilitate the health care units' administration. The store and the processing of the patients' personal data and examination results in data bases and expert systems aids the decision making. The appearance of the electronic health care improves the people informativeness in a low price.

The construction of models of the parallel processes which flow in medicine allows their full and correct understanding. This leads to minimization of the waiting times and the times for decision making. The simulation of the made models with real experimental data allows status evaluations, prognosis for critical moments and situations, planning of the medical personnel, material equipment and specialized apparatuses allocation. Examination of different what-if analyses of real situations give possibility for finding of the healthcare system's bottlenecks.

The GN-models of the organizational and administrative processes in hospital institutions are in several directions:

1. patient flow modelling;
2. information flow modelling;
3. modelling of the resources allocation.

Some of these models represent the processes in a specific health care unit—for example patient flow in a clinic. Thus the GN allows accumulation of data, which concern particular patient—used materials and specialized apparatuses, made examinations, engaged medical stuff in the rehabilitation process and so on, all traced into the time. Using the results of the GNs work it is possible to make conclusions about the dynamics of the process, number of the treated patients, case history, economical assessment of outlays. These results could be used in the process of decision making and further diagnostics.

5.1 Patient Flow Modelling

Planning of hospital resources has always been a matter of great importance. One of the major elements in improving efficiency in the delivery of health care services is optimizing the patient flow and length of stay. Modelling patient flow in health care systems is considered to be vital in understanding the operation of the system and may therefore prove to be useful in improving the functionality of the health care system. Better understanding of system operation is needed to predict and support health care activities in every medical clinic. The understanding and modelling of patient flow can offer information to health care providers about the patients disease progression or recovery status. The effective resource allocation and capacity planning is dependant on patient flow because it is equivalent to the need of health care services. If there is an understanding of patient flows, this knowledge can be used to improve and optimize the activities of health care system. And the resource planning, scheduling and utilization optimization can affect the quality of health care services and patient flow.

In [54] it is proved, with no doubt, the big need of simulation models of health care institutions. The aim of this paper is to asses the benefits of a model that examines the impact of bed blockage, occupancy and emptiness on patient flow in a geriatric inpatient unit. Departments of geriatric medicine provide an acute, rehabilitative and long-stay service for older people with complex medical and social needs. Simulation modelling gives an opportunity for predicting the situation of bed crisis in some months of the year or for epidemics [137]. That is why when there is insufficient amount of beds available to admit ill people in hospitals, queues are formed. This may be fatal for some patients. The movement of patients through hospitals can be seen to occur in streams. Wards such as acute, rehabilitation and long stay are dependent on the dimensions of time and performance. But the availability of hospital beds for admission depends on patients leaving the system. In [137] it is demonstrated using simulation model that the cause of the crisis is a breakdown in the discharge of dependent patients from the medium-stay stream. Clinically, bed blocking occurs when patients are kept waiting in one ward or hospital until free beds are available in a more suitable ward or hospital. For instance, rehabilitation or long—stay patients can be kept waiting in the acute wards until beds become available elsewhere, effectively blocking the availability of the beds for other patients.

A patient flow begins when a patient needs health consultation and goes to his/her personal doctor, who gives him/her diagnose, or when the patient is admitted to a health care system. Similarly, when the patient is discharged from a health care unit this is the patient flow exit. Between these two points there is a set of conditions, activities, services, or locations that the patient may pass. Within these points, the patient requires a variety of health care resources (e.g., beds, examining rooms, physicians, nurses, medical apparatuses and procedures). That is why the patient flow can be depicted as a network. The basic network elements represent the patient statuses in health care system (nodes) and indicate the flow between nodes (arcs). An important characteristic of the patient flow is its random nature [55]. For a given health care service, not all of the elements may be applicable to all patients. And the time that patients spend at each node and in the whole network also contains a degree of randomness. Once patients state is estimated it is possible to assign what resources (for instance medical staff and equipment) will be required. Of course health care clinic has capacity and resource limitations, so queuing for services occurs. Queuing characteristics, such as time in the system and traffic intensity, correspond to the patient flow characteristic.

The study of problems with patient flow distribution has priority importance because it is one of the major elements in improving efficiency in the delivery of health care services. GNs are quite promising for representing patient flow and cases history. Understanding of patient flow is needed to support health care activities in every medical clinic. The effective resource allocation and capacity planning are dependant on the patient flow because it is equivalent to the need of health care services. The patient flow optimization can affect quality of health care services and can have positive effects on patient and clinical staff satisfaction.

Some other GN-models of patient flow are presented in [128–132] .

5.2 Information Flow Modelling

Although confidentiality issues have long existed before the arrival of the computer and the Internet, the use of IT that is capable of transmitting large amounts of data in very short time intervals, and of bypassing the conventional physical barriers and safeguards, certainly heightens public anxiety. Based on the medical needs of an individual, several medical professionals (of different specialties) may have been visited by him for medical care. Each of the medical professionals visited keeps information about their patients. Similarly, hospitals keep all the records for patients that require hospitalization for treatment. In addition, the patients fill their prescriptions at different pharmacies. All the bits and pieces of information that are scattered at various places may be necessary for providing effective healthcare to an individual. There are several ways of keeping this information handy and ready for use when needed. It is not practical for every individual to carry this information with him in paper form all the time. Also, legal aspects associated with the medical records require that the medical information should not be altered. Therefore, all mechanisms used for gathering, disseminating, or transporting medical information must adhere to all the legal requirements. Advances in information technology have provided many options for individuals to have their medical history available whenever it is needed.

The information systems and computer networks allow the information of the patient to be accessible for short periods of time even on long distances and they facilitate the putting of diagnose. For that purpose the development of secure and fast connection is required. Personal computers in a specific healthcare unit have to be connected in a local network and connection between healthcare units is also needed. Building a network in a healthcare unit can improve integration of clinical, financial, and administrative data for the various stakeholders, improve patient outcomes, increase administrative efficiency and can reduce the likelihood of medical errors and lower overall costs.

The purpose of the modelling of the information flows is gaining knowledge about the happening inside the health care system. The need for concise and accurate capture or representation of the patient flow and length of stay information assets are important for the delivery of effective and in time healthcare services. Modelling of the processes in the healthcare domain offers the opportunity to detect bottlenecks and to suggest effective changes in case of critical condition. In this way the knowledge and the experience gained from experts could become available to all stakeholders concerned in the quality and effectiveness of healthcare services and contribute towards more effective resource allocation and use.

A GN-model for representation of links and interactions between particular wards in a hospital as well as separate sections in a single ward are described in [99, 100]. The GN-model of the information net is needed, because as the investigations shows it is important that health policy makers and doctors have accurate information about a safety net and the data considering their patients. With such an information system the whole available data for the diseases, symptoms, case history of the patients—their disease progression or recovery status as well as test results, will be easily accessible for the specialists who work in the health care sphere. It is clear that this information play a critically important role in decision making and making primary care available. Information GNs could be a software tool for modelling and simulating real time parallel processes witch runs in a single health care unit as well as in a whole hospital system. The purpose is to develop information technology with which we could easily represent and simulate complex health care systems and apply to medicine and pharmacy.

There exist different ways for the construction of a network architecture in the frames of particular healthcare unit and between the separate medical institutions. Having in mind the area which is to be covered, the optimal trade off between cost and quality has to be derived. This includes decision making for: number and parameters of the servers, their disposal, the connections between them, the communication protocol, the time intervals for updating the information, etc. On that basis are developed two GN-models that represent a process of information exchange (inserting and requesting data) between several healthcare units [99] and within particular medical centre [100]. In [99] there is one global server-repository as in the case of data warehouses, which will save all the data for the patients. Every unit works on its own server-source, which communicates with the central one and sends the data to it.

5.3 *Modelling of the Resources Allocation*

Health care technology is subject to constant improvement. This is often accompanied by complex interactions between result, efficiency, staff training, equipment maintenance, patient risk and cost of treatment. Implementation of novelties is a complex task requiring the evaluation of the specifics and the benefits and risks related to the most part of medical technology.

Modelling of the processes which flow in the health care system could be used for planning of the resources allocation (buildings, equipment and specialists), as well as for determination of the bottlenecks in the system. Beds, personnel work load and available apparatuses determine the capacity of a given unit. Built model of the system could answer to the question if there is a free position for a new patient or no.

A GN-model of Intensive Care Unit (ICU) workflow is presented in [132]. The goal of the workflow organization in an ICU is to assign a medical team and specialized equipment to each patient. At any moment the department is in a certain state with respect to available beds, patients condition, available staff and equipment. This information is stored in the unit's databases. The medical staff database contains information on the qualifications and work load of the staff. The hierarchy is respected when making a decision in the unit the decision is made by the highest-ranking authority present at the moment. For example, if the head of the unit is absent, the responsibility is transferred to the department head, while if he is in turn not available to the on duty or in charge physician. Despite this strict hierarchy, there are cases when the decision could only be made by the department or unit head. Dedicated databases are used to store the protocols with recommendations for specific actions, as well as past treatments and conditions of the patients.

The description so far reflects the limitation on staff workload only that is, bed or equipment availability were assumed sufficient. However, the amount of beds is actually always limited. It may be necessary to discharge a patient in an unstable status with high risk due to the need to accept another. A decision of this type could only be made by the head of the unit or the department. In most cases, equipment is also limited. This influences the work flow in the department and may lead to difficult decisions. The GN-models describing the process of resource allocation could be used to determine the optimum level of staff and equipment [30, 40, 63, 69, 91, 115, 130, 133].

6 Modelling of Telecare/Telehealth

Telehealth is the remote monitoring of patients' vital signs and symptoms in their own home—proven to enhance the quality of life and clinical outcomes for people with long-term conditions. It also helps people understand and manage their health, enabling them to stay out of hospital and enjoy life with their family and friends.

The evaluation of telehealth/telecare solutions of UK Department of Health's Whole System Demonstrator Program shows the following results:

Commissioning benefits:

- 45 % reduction in mortality rates;
- 20 % reduction in emergency admissions;
- 15 % reduction in A&E visits;
- 14 % reduction in elective admissions;
- 14 % reduction in bed days;
- 8 % reduction in tariff costs.

Clinical benefits:

- Encourages self-management;
- Enables early identification of exacerbations;

- Aids medication compliance;
- Identifies trends over time to aid proactive care planning;
- Helps clinicians make more informed medication management decisions;
- Supports efficient caseload management (Tunstall Healthcare, see [143]).

GNs have been used as a tool for modeling processes in telecare and telemedicine [2–4, 70]. A GN model of telecare is presented in [3]. It can be used as a decision support tool to enhance the work of the specialists in the telehealth center. Smart filtering of alarm messages is proposed in [4]. In the model developed in [70] traces the logical stages of the final part of the process of communication between the sensors connecting mobile adult patients and the staff of the respective hospital unit. The developed model can be used for simulation of the processes of decision making of the appropriate specialists, who must either visit the respective adult patient or transport him/her to the hospital unit. The model permits simulation of different scenarios e.g. the situation, in which many patients simultaneously require medical assistance. Finally, the model in [2] is an example of telemedicine based on body temperature sensors.

7 GN Model of Telemedicine for People with Diabetes

Diabetes mellitus (DM) includes a group of metabolic diseases, characterized by high blood glucose, either because the pancreas does not produce enough insulin (absolute insulin deficiency), or because cells do not respond to the insulin that is secreted (insulin resistance) or both. There are two main types of DM:

Type 1 DM results from the body's failure to produce insulin because of autoimmune destruction of insulin producing cells in the pancreas and requires insulin injections at least 4 times daily or a use of insulin pump. Hypoglycemia and weight gain are the most common adverse effects of insulin therapy.

Type 2 DM results from insulin resistance, a condition in which cells fail to use insulin properly because of metabolic disturbances, most frequently caused by obesity. In the early disease stages, insulin production is normal or increased in absolute terms, but disproportionately low for the degree of insulin sensitivity, which is typically reduced. However the ability of the pancreatic β-cells to release insulin in phase with rising glycemia, are profoundly compromised [142]. In the beginning type 2 diabetes is treated with oral medications which either decrease insulin resistance or increase insulin secretion. Treatment choices depend on many factors, most important of which are body weight and concomitant diseases. Some of the oral antidiabetic drugs can also induce hypoglycemia. At the end stage of the disease when absolute insulin deficiency is developed, patients usually need insulin injections 1–4 times daily. Weight reduction improves glycemic control and other cardiovascular risk factors in patients with type 2 diabetes. Modest weight loss (5–10 %) contributes meaningfully to achieving improved glucose control. Accordingly, establishing a goal of weight reduction, or at least weight maintenance, is recommended

[141]. On the other hand most of the drugs used to treat diabetes, including insulin can lead to significant weight gain. This warrants individualisation of treatment choices, especially in patients with obesity.

Ideally, the principle of diabetes treatment is the achievement of as normal a glycemic profile as possible without unacceptable weight gain or hypoglycemia. The American Diabetes Assotiation Standards of Medical Care in Diabetes recommends lowering HbA 1c to 7.0 % in most patients to reduce the incidence of microvascular disease. This can be achieved with a mean plasma glucose of 8.3−8.9 mmol/l (150−160 mg/dL); ideally, fasting and premeal glucose should be maintained at <7.2 mmol/l (<130 mg/dL) and the postprandial glucose at <10 mmol/l (<180 mg/dL) [139]. Plasma glucose <3.9 mmol/l in patients with diabetes is generally considered hypoglycemia. Patients on insulin therapy and oral agents that can cause hypoglycemia should be instructed in techniques for self-monitoring of blood glucose. Initially, blood glucose levels should be checked at least four times a day in patients taking multiple insulin injections. Generally, these measurements are taken before each meal and at bedtime. In addition, patients should be taught to check their blood glucose level whenever they develop symptoms that could represent a hypoglycemic episode [140].

Acute complications of diabetes.

Hypoglycemia is a life-threatening acute complication of antidiabetic treatment. Clinical hypoglycemia is, by definition, a plasma glucose concentration low enough to cause symptoms or signs, including impairment of brain function. The glycemic thresholds for symptoms and signs of hypoglycemia are dynamic; for example, they shift to lower plasma glucose concentrations in patients with recurrent hypoglycemia and to higher concentrations in those with poorly controlled diabetes. All of the manifestations of hypoglycemia are rapidly relieved by glucose administration. Patients with symptoms of hypoglycemia who are conscious and able to swallow should eat or drink orange juice, glucose tablets, or any sugar-containing beverage or food. In patients that are unconscious the preferred treatment is 50 mL of 50 % glucose solution given rapidly over 3–5 min intravenously. If trained personnel are not available to administer intravenous glucose, the treatment of choice is for a family member or friend to administer 1 mg of glucagon intramuscularly, which usually restores the patient to consciousness within 10–15 min [141]. If a patient develops severe hypoglycemia after use of long-acting antidiabetic medications, that induce insulin secretion, he should be observed in hospital for at least 24 h to prevent recurrent hypoglycemia.

Diabetic ketoacidosis and diabetic hyperosmolar coma are acute complications of diabetes, that require hospital treatment. As opposed to the acute onset of hypoglycemic coma, diabetic ketoacidosis is usually preceded by a day or more of polyuria and polydipsia associated with marked fatigue, nausea, and vomiting. Eventually, mental stupor ensues and can progress to frank coma. High blood glucose (usually >15−18 mmol/l), ketonuria, ketonemia, low arterial blood pH, and low plasma bicarbonate (5−15 mEq/L) are typical laboratory findings in diabetic

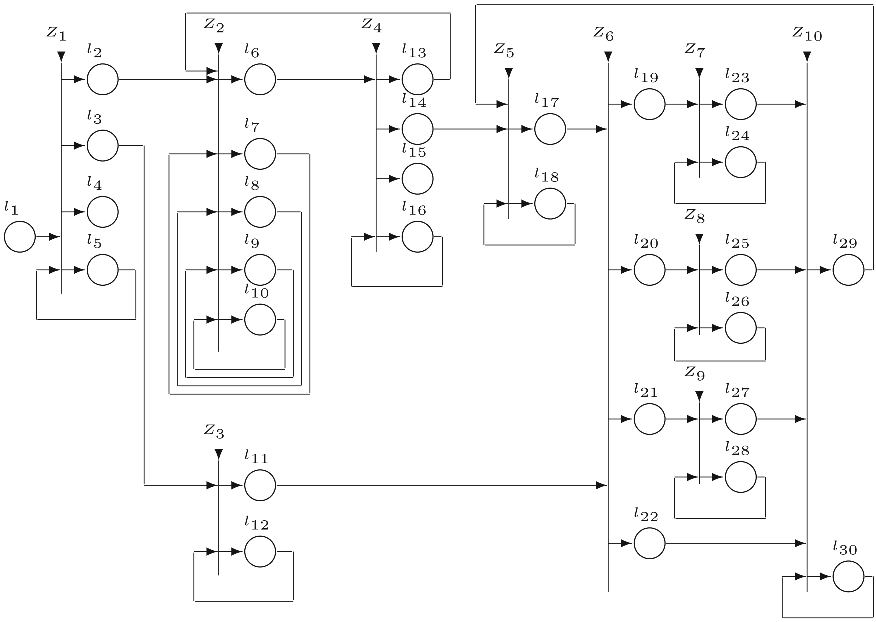


Fig. 1 GN model of telemedicine for people with diabetes

ketoacidosis. The onset of the hyperglycemic, hyperosmolar, nonketotic state may be preceded for days or even weeks by symptoms of weakness, polyuria, and polydipsia. A history of reduced fluid intake is common, whether due to inappropriate absence of thirst, gastrointestinal upset, or, in the case of elderly or bedridden patients, lack of access to water. In diabetic hyperosmolar state there are no ketones in the urine but the blood glucose is very high (>25−30 mmol/l).

The telehealth package for people living with diabetes consists of a blood pressure monitor, weight scale, pulse oximeter and blood glucose monitor. Intelligent health interview is also a necessity (LifeLink Telehealth, see [144]).

Telemedicine has been widely used to bring healthcare to patients living in distant locations. In [42] it is demonstrated how modem technologies can be used as a tool for providing telemedicine for people with diabetes. This approach has been proven to be cost—effective [67, 68]. On the basis of the models presented in [2–4, 70], here we propose a GN model of telemedicine for people with diabetes. The GN consists of ten transitions (see Fig. 1). They have the following meaning:

- Z_1 represents the patients.
- Z_2 represents the collecting of data from the sensors.
- Z_3 represents the process of taking a health interview from the patient.
- In Z_4 the signals from the sensors are checked for correctness.
- Z_5 represents the database with the patients' history and the decisions taken by the specialists in the telemedicine center.
- Z_6 represents the differentiation of the signals depending on the glucose level.

- In transitions Z_7, Z_8 and Z_9 all data which is required for the telemedicine specialists to take a decision is gathered.
- Z_{10} represents the process of decision making in the telemedicine center.

Eight different types of tokens are used.

- Tokens $\pi_1, \pi_2, \dots, \pi_n$ represent the n patients who are monitored by the telemedicine center. They stay in place l_5 in the initial time moment with initial characteristic *"name of the patient, location"*.
- Tokens $\nu_1, \nu_2, \dots, \nu_n$ represent the blood pressure monitors. In the initial time moment they stay in place l_7 with initial characteristic *"name of the patient, data about the device"*.
- Tokens $\gamma_1, \gamma_2, \dots, \gamma_n$ represent the glucose meters. In the initial time moment they stay in place l_8 with initial characteristic *"name of the patient, data about the device"*.
- Tokens $\omega_1, \omega_2, \dots, \omega_n$ represent the weight scales. In the initial time moment they stay in place l_9 with initial characteristic *"name of the patient, data about the device"*.
- Token ζ stays in place l_{12} with initial characteristic *"health interview"*.
- Token α stays in place l_{16} with initial characteristic *"criterion for the correctness of the signals"*.
- Token β stays in place l_{18} with initial characteristic *"database with data about the patients and the decisions taken by the telemedicine person"*.
- Tokens $\delta_1, \delta_2, \dots, \delta_k$ represent the telemedicine specialists (telemedicine nurses) who make decisions in the telemedicine center. They stay in place l_{30} in the initial time moment with characteristic *"name, decisions taken, duration of the shift"*.

During the functioning of the net new π-tokens may enter the net through place l_1. These new tokens represent the new patients who are included in the model. Also, some of the π-tokens in place l_5 may leave the net through place l_4 which reflects the fact that the patients corresponding to these tokens are no longer monitored by the system.

The proposed GN is a reduced one, i.e. not all of the components from the definition of GN are present (see [5]). What follows is a description of the transitions of the net.

$$Z_1 = \langle \{l_1, l_5\}, \{l_2, l_3, l_4, l_5\}, r_1, \Box_1 \rangle,$$

where

$$r_1 = \begin{array}{c|cccc} & l_2 & l_3 & l_4 & l_5 \\ \hline l_1 & true & false & false & true \\ l_5 & W_{2,5} & W_{5,3} & W_{5,4} & W_{5,5} \end{array}$$

and

$W_{5,2}$ =*"sensor data about the current patient must be sent to the telemedicine center"*;
$W_{5,3}$=*"health interview with the current patient has to be conducted"*;

$W_{5,4}$= *"the current patient must leave the system"*;
$W_{5,5} = \neg W_{5,4}$.
Here and below $\neg W_{i,j}$ is the negation of the predicate $W_{i,j}$.
$\square_1 = \vee(l_1, l_5)$.

When the truth value of the predicate $W_{5,2}$ becomes *true* the current π-token in place l_5 splits into two identical tokens—the original that remains in l_5 and a new one π' which enters l_2 without new characteristic. The new π-token in l_1 splits into two identical tokens one of which enters place l_5 with characteristic *"name of the patient, location"*. The other one enters place l_2 with characteristic *"name of the patient, data about the sensors"*. When the truth value of $W_{5,3}$ is true the π-token splits into two identical tokens—the original which stays in l_5 and a new π'' which enters l_3 without new characteristic.

$$Z_2 = \langle \{l_2, l_7, l_8, l_9, l_{10}, l_{13}\}, \{l_6, l_7, l_8, l_9, l_{10}\}, r_2, \square_2 \rangle,$$

where

$r_2 =$

	l_6	l_7	l_8	l_9	l_{10}
l_2	*false*	$W_{2,7}$	$W_{2,8}$	$W_{2,9}$	$W_{2,10}$
l_7	$W_{7,6}$	*true*	*false*	*false*	*false*
l_8	$W_{8,6}$	*false*	*true*	*false*	*false*
l_9	$W_{9,6}$	*false*	*false*	*true*	*false*
l_{10}	$W_{10,6}$	*false*	*false*	*false*	$W_{10,10}$
l_{13}	*false*	*false*	*false*	*false*	*true*

and

$W_{2,7}$= *"the current π' -token represents a new patient"*;
$W_{2,8} = W_{2,9} = W_{2,7}$;
$W_{2,10} = \neg W_{2,7}$;
$W_{7,6}$= *"the blood pressure of the current patient has been measured"*;
$W_{8,6}$= *"for the current γ-token there is corresponding π'-token in place l_{10}"* & *"the glucose level of the patient corresponding to the current γ-token has been measured"*;
$W_{9,6}$= *"the weight of the patient corresponding to the current ω-token has been measured"*;
$W_{10,6}$= *"the glucose level of the current patient has been measured"*;
$W_{10,10} = \neg W_{10,6}$.
$\square_2 = \vee(l_2, l_7, l_8, l_9, l_{10}, l_{13})$.

If the current π'-token in place l_2 represents a new patient, then it splits into three tokens $\nu_i, \gamma_i, \omega_i$ which enter places l_7, l_8 and l_9 respectively with characteristic *"name of the patient, data about the respective sensor"*.

When the glucose level the patient has been measured the current γ-token in l_8 splits into two tokens—the original and a new identical one γ' which enters place l_6 where it obtains the characteristic *"glucose level of the patient"*. When the glucose level of the patient corresponding to the π'-token in l_{10} has been measured, this same π'-token enters place l_6 where it merges with the γ-token into a new π'-token.

When the truth value of the predicate $W_{7,6}$ becomes *true* the current ν-token in l_7 splits into two tokens—the original which remains in l_7 and new identical one ν' which enters l_6 with characteristic *"blood pressure of the corresponding patient"*.

When the truth value of the predicate $W_{9,6}$ becomes *true* the current ω-token splits into two tokens—the original which remains in l_9 and new identical one ω' which enters place l_6 with characteristic *"weight of the corresponding patient"*.

$$Z_3 = \langle \{l_3, l_{12}\}, \{l_{11}, l_{12}\}, r_3, \square_3 \rangle,$$

where

$$r_3 = \begin{array}{c|cc} & l_{11} & l_{12} \\ \hline l_3 & true & false \\ l_{12} & false & true \end{array}$$

$\square_3 = \wedge(l_3, l_{12})$.

In l_{11} the π''-tokens obtain the characteristic *"answers to the interview questions"*.

$$Z_4 = \langle \{l_6, l_{16}\}, \{l_{13}, l_{14}, l_{15}, l_{16}\}, r_4, \square_4 \rangle,$$

where

$$r_4 = \begin{array}{c|cccc} & l_{13} & l_{14} & l_{15} & l_{16} \\ \hline l_6 & W_{6,13} & W_{6,14} & W_{6,15} & false \\ l_{16} & false & false & false & true \end{array}$$

and

$W_{6,13} =$ *"the criterion shows that the signal has to be confirmed"*;
$W_{6,14} =$*"the criterion shows that the signal is correct"*;
$W_{6,15} =$*"the criterion shows that the signal is incorrect"*.
$\square_4 = \wedge(l_6, l_{16})$.

In places l_{13}, l_{14} and l_{16} the tokens do not obtain new characteristics. In place l_{15} the tokens obtain the characteristic *"incorrect signal"*.

$$Z_5 = \langle \{l_{14}, l_{18}, l_{29}\}, \{l_{17}, l_{18}\}, r_5, \square_5 \rangle,$$

where

$$r_5 = \begin{array}{c|cc} & l_{17} & l_{18} \\ \hline l_{14} & W_{14,17} & W_{14,18} \\ l_{18} & false & true \\ l_{29} & false & true \end{array}$$

and

$W_{14,18}$ = "*the current token in* l_{14} *is of type* ω";
$W_{14,17} = \neg W_{14,18}$.
$\square_5 = \vee(\wedge(l_{14}, l_{18}), l_{29})$.

The ω-token in place l_{14} enters l_{18} where it unites with the β-token. The other type of tokens enter l_{17} with characteristic *"data about the current patient"*.

$$Z_6 = \langle \{l_{11}, l_{17}\}, \{l_{19}, l_{20}, l_{21}, l_{22}\}, r_6, \square_6 \rangle ,$$

where

$$r_6 = \begin{array}{c|cccc} & l_{19} & l_{20} & l_{21} & l_{22} \\ \hline l_{11} & W_{11,19} & W_{11,20} & W_{11,21} & false \\ l_{17} & W_{17,19} & W_{17,20} & W_{17,21} & W_{17,22} \end{array}$$

and

$W_{11,19}$ = "*there is* π' *token in place* l_{24} *which is corresponding to the current* π'' *in place* l_{11}";
$W_{11,20}$ = "*there is* π' *token in place* l_{26} *which is corresponding to the current* π'' *in place* l_{11}";
$W_{11,21}$ = "*there is* π' *token in place* l_{28} *which is corresponding to the current* π'' *in place* l_{11}";
$W_{17,19}$ = "*the glucose level of the current patient is less than or equal to* 4 mmol/l";
$W_{17,20}$ = "*the glucose level of the current patient is greater than* 4 mmol/l *and less than or equal to* 10 mmol/l";
$W_{17,21}$ = "*the glucose level of the current patient is greater than* 10 mmol/l *and less than or equal to* 18 mmol/l";
$W_{17,22}$ = "*the glucose level of the current patient is greater than or equal to* 18 mmol/l".
$\square_6 = \vee(l_{11}, l_{17})$.

In places l_{19}, l_{20}, l_{21} and l_{22} the tokens obtain characteristic *"time of arrival of the signal"*.

$$Z_7 = \langle \{l_{19}, l_{24}\}, \{l_{23}, l_{24}\}, r_7, \square_7 \rangle ,$$

where

$$r_7 = \begin{array}{c|cc} & l_{23} & l_{24} \\ \hline l_{19} & W_{19,23} & W_{19,24} \\ l_{24} & W_{24,23} & W_{24,24} \end{array}$$

and

$W_{19,23}$ = *"the current patient is unconscious"*;
$W_{19,24} = \neg W_{19,23}$;
$W_{24,23}$ = *"all required data about the patient has been collected or the maximum time of waiting has been reached"*;

$W_{24,24} = \neg W_{24,23}$.
$\square_7 = \vee(l_{19}, l_{24})$.

In place l_{24} the tokens obtain the characteristic *"waiting for blood pressure measurement and/or results from the health interview; duration of the waiting"*. In place l_{23} the tokens do not obtain new characteristic.

$$Z_8 = \langle \{l_{20}, l_{26}\}, \{l_{25}, l_{26}\}, r_8, \square_8 \rangle ,$$

where

$$r_8 = \begin{array}{c|cc} & l_{25} & l_{26} \\ \hline l_{20} & W_{20,25} & W_{20,26} \\ l_{26} & W_{26,25} & W_{26,26} \end{array}$$

and

$W_{20,25}$ =*"the current patient is unconscious"*;
$W_{20,26} = \neg W_{20,25}$;
$W_{26,25}$ =*"all required data about the patient has been collected or the maximum time of waiting has been reached"*;
$W_{26,26} = \neg W_{26,25}$.
$\square_8 = \vee(l_{20}, l_{26})$.

In place l_{26} the tokens obtain the characteristic *"waiting for blood pressure measurement and/or results from the health interview; duration of the waiting"*. In place l_{25} the tokens do not obtain new characteristic.

$$Z_9 = \langle \{l_{21}, l_{28}\}, \{l_{27}, l_{28}\}, r_9, \square_9 \rangle ,$$

where

$$r_9 = \begin{array}{c|cc} & l_{27} & l_{28} \\ \hline l_{21} & W_{21,27} & W_{21,28} \\ l_{28} & W_{28,27} & W_{28,28} \end{array}$$

and

$W_{21,27}$ =*"the acetone of the current patient is positive"*;
$W_{21,28} = \neg W_{21,27}$;
$W_{28,27}$ =*"all required data about the patient has been collected or the maximum time of waiting has been reached"*;
$W_{28,28} = \neg W_{28,27}$.
$\square_9 = \vee(l_{21}, l_{28})$.

In place l_{28} the tokens obtain the characteristic *"waiting for interview results; duration of the waiting"*. In place l_{27} the tokens do not obtain new characteristic.

$$Z_{10} = \langle \{l_{22}, l_{23}, l_{25}, l_{27}, l_{30}\}, \{l_{29}, l_{30}\}, r_{10}, \square_{10} \rangle ,$$

where

$$r_{10} = \begin{array}{c|cc} & l_{29} & l_{30} \\ \hline l_{22} & true & false \\ l_{23} & true & false \\ l_{25} & true & false \\ l_{27} & true & false \\ l_{30} & false & true \end{array}$$

and

$\square_{10} = \wedge(\vee(l_{22}, l_{23}, l_{25}, l_{27}), l_{30})$. In places l_{24}, l_{26} and l_{28} the π''-tokens, the γ'-tokens and the π'-tokens corresponding to one and the same patient merge into a new π'-token. In place l_{29} the tokens obtain the characteristic *"decision taken by the telemedicine person"*. In place l_{30} the δ-tokens obtain the characteristic *"decision taken, duration of the shift"*.

8 Conclusion

The modelling and the simulation of the processes in the health care system as a whole allow better description, control in real time and prognosis. The usage of GNs in medicine holds out an opportunity for a new approach toward modelling and simulation of the information, patient and work-load flows in health care units and health care system. The so made simulation models give a new look over the problems related with restructuring, managing, planning and organization of the health care services. The GN models developed in medicine contribute to:

- early finding of pathological deviations and determining of the reasons;
- start from simpler methods (disease history, thorough examination, simple laboratory tests), available to every physician at each level of the health-care system and if necessary, proceed to newer and more expensive methods;
- showing (using) the most informative methods of study and treatment at a given stage of treatment. This, depending on the level of the physician, facilitates the generation of diagnosis or approximation to the most probable one;
- avoiding redundant studies, assist the decision of using more expensive methods; direct the patient to the corresponding specialist or hospital for precise assessment of his/her status; timely initiation and proper carrying out of the treatment and follow-up;
- determining the bottlenecks for the process of providing health care services and evaluating how changes to clinic design increase or reduce queues, time in system, and number of patients in the clinic (the different what-if scenarios could provide useful information to the hospital administrators for making management decision).

On the basis of the GN model of telemedicine for people with diabetes described in this paper a decision support tool can be developed. The model can be easily extended to include estimations of the costs of the telemedicine center. Computer simulation of the model can be used to determine the optimal number of specialists in the telemedicine center.

Appendix: Short Remark on Generalized Nets

GNs [5, 9] are extensions of Petri Nets [73]. They are defined in a way that is principally different from the ways of defining the other types of Petri nets. We shall first give an example of a GN and make remarks about the notation. A GN is shown in Fig. 2. The *places* are marked with ◯. Each part of the net which looks like the one shown on Fig. 3., is called *transition* (more precisely graphic structure of transition). Transition's conditions are denoted by |. GNs, like other nets, contain tokens which are transferred from place to place. Every token enters the net with an initial characteristic. During each transfer, the token receives new characteristics. So, they accumulate their *"history"*. This is the first essential difference with the other types of Petri nets.

Every GN-place has at most one arc entering and at most one arc leaving it. The places with no entering arcs are called *input places* for the net (l_1, l_2 on Fig. 2.) and those with no leaving arcs are called *output places* (l_{14} and l_{15} on Fig. 2.). The *input places* are always at the transition's left, and the *output places* are always at the

Fig. 2 Generalized net

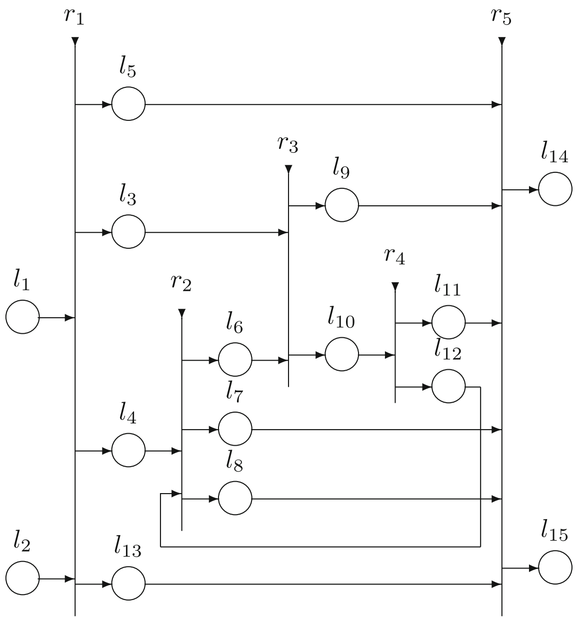
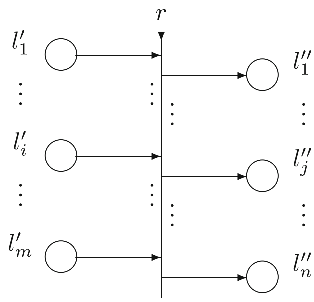


Fig. 3 Transition



transition's right side. When tokens enter the input place of a transition, it becomes *potentially fireable* and at the moment of their transfer towards the transition's output places, it is being *fired.* The transition becomes active at a given time-moment and remains active up to another predefined moment.

The second basic difference between GNs and the ordinary Petri nets is the "place—transition" relation. Here, transitions are objects of a more complex nature. A transition may contain m input and n output places where $m, n \geq 1$.

The third basic difference is related to the time during which the GN functions. The time *can be* determined from some global time-scale and in this case the net is not invariant about the time-parameters. When we have GN models of some (different, but connected) processes that flow in parallel at time, we can use many time-scales or a single one, accounting the moments of the separate events in the processes. In the present form of the GN-definition, time is discrete. It increases with discrete steps. We can see the status of the GN model in each current time-moment.

Formally, every transition is described by a seven-tuple:

$$Z = \langle L', L'', t_1, t_2, r, M, \Box \rangle,$$

where:

(**a**) L' and L'' are finite, non-empty sets of places (the transition's input and output places, respectively); for the transition in Fig. 3 these are

$$L' = \{l'_1, l'_2, \ldots, l'_m\}$$

and

$$L'' = \{l''_1, l''_2, \ldots, l''_n\};$$

(**b**) t_1 is the current time-moment of the transition's firing;

(**c**) t_2 is the current value of the duration of its active state;

(**d**) r is the transition's *condition* determining which tokens will transfer from the transition's inputs to its outputs. Parameter r has the form of an IM:

$$r = \begin{array}{c|c} & l''_1 \ \dots \ l''_j \ \dots \ l''_n \\ \hline l'_1 & \\ \vdots & r_{i,j} \\ l'_i & (r_{i,j} \ - \ \text{predicate}) \\ \vdots & (1 \le i \le m, 1 \le j \le n) \\ l'_m & \end{array} ;$$

where $r_{i,j}$ is the predicate which expresses the condition for transfer from the ith input place to the jth output place. When $r_{i,j}$ has truth-value "*true*", then a token from the ith input place can be transferred to the jth output place; otherwise, this is impossible;

(**e**) M is an IM of the capacities of transition's arcs:

$$M = \begin{array}{c|c} & l''_1 \ \dots \ l''_j \ \dots \ l''_n \\ \hline l'_1 & \\ \vdots & m_{i,j} \\ l'_i & (m_{i,j} \ge 0 - \ \text{natural number or } \infty) \\ \vdots & (1 \le i \le m, 1 \le j \le n) \\ l'_m & \end{array} ;$$

(**f**) $\square$ is called transition type and it is an object having a form similar to a Boolean expression. It may contain as variables the symbols that serve as labels for transition's input places, and it is an expression constructed of variables and the Boolean connectives $\wedge$ and $\vee$ determining the following conditions:

$\wedge(l_{i_1}, l_{i_2}, \dots, l_{i_u})$ – every place $l_{i_1}, l_{i_2}, \dots, l_{i_u}$ must contain at least one token,

$\vee(l_{i_1}, l_{i_2}, \dots, l_{i_u})$ – there must be at least one token in the set of places $l_{i_1}, l_{i_2}, \dots, l_{i_u}$, where $\{l_{i_1}, l_{i_2}, \dots, l_{i_u}\} \subset L'$.

When the value of a type (calculated as a Boolean expression) is "*true*", the transition can become active, otherwise it cannot.

The ordered four-tuple

$$E = \langle\langle A, \pi_A, \pi_L, c, f, \theta_1, \theta_2\rangle, \langle K, \pi_K, \theta_K\rangle, \langle T, t^0, t^*\rangle, \langle X, \Phi, b\rangle\rangle$$

is called a *Generalized Net* if:

(**a**) A is a set of transitions (see above);

(**b**) π_A is a function giving the priorities of the transitions, i.e., $\pi_A : A \to \mathcal{N}$;

(**c**) π_L is a function giving the priorities of the places, i.e., $\pi_L : L \to \mathcal{N}$, where

$$L = pr_1 A \cup pr_2 A$$

and obviously, L is the set of all GN-places;

(**d**) c is a function giving the capacities of the places, i.e., $c : L \to \mathcal{N}$;

(**e**) f is a function that calculates the truth values of the predicates of the transition's conditions;

(**f**) θ_1 is a function giving the next time-moment, for which a given transition Z can be activated, i.e., $\theta_1(t) = t'$, where $pr_3 Z = t, t' \in [T, T + t^*]$ and $t \leq t'$; the value of this function is calculated at the moment when the transition terminates its functioning;

(**g**) θ_2 is a function giving the duration of the active state of a given transition Z, i.e., $\theta_2(t) = t'$, where $pr_4 Z = t \in [T, T + t^*]$ and $t' \geq 0$; the value of this function is calculated at the moment when the transition starts functioning;

(**h**) K is the set of the GN's tokens. In some cases, it is convenient to consider this set in the form

$$K = \bigcup_{l \in Q^I} K_l,$$

where K_l is the set of tokens which enter the net from place l, and Q^I is the set of all input places of the net;

(**i**) π_K is a function giving the priorities of the tokens, i.e., $\pi_K : K \to \mathcal{N}$;

(**j**) θ_K is a function giving the time-moment when a given token can enter the net, i.e., $\theta_K(\alpha) = t$, where $\alpha \in K$ and $t \in [T, T + t^*]$;

(**k**) T is the time-moment when the GN starts functioning; this moment is determined with respect to a fixed (global) time-scale;

(**l**) t^0 is an elementary time-step, related to the fixed (global) time-scale;

(**m**) t^* is the duration of the GN functioning;

(**n**) X is a function which assigns initial characteristics to every token when it enters input place of the net;

(**o**) Φ is a characteristic function that assigns new characteristics to every token when it makes a transfer from an input to an output place of a given transition;

(**p**) b is a function giving the maximum number of characteristics a given token can receive, i.e., $b : K \to N$.

For the algorithms of transition and GN functioning the reader can refer to [9].

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