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# Dynamic Model of Intensive Care Unit Workflow based on Generalized Nets

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***Abstract:*** *Every* ***intensive care unit*** *(ICU) admits critically ill patients with disturbed vitally important functions. Time is a critical factor with such patients and the optimum behaviour of the medical team is decisive. They require optimised distribution of the staff and material resources, hence an adequate model of the structure and activities in an ICU is needed. Such a model was built using* ***generalized nets*** *(GNs).*
*The workflow presented as a GNs-model is based on principles and prerequisites typical of ICU. Structure of the information included in the model: the updated information on the state of the ICU (occupancy rate of the hospital beds, the state of the patients, the available physicians and nurses, and their distribution for the concrete patients, available material facilities) is supported by specialised databases. There also exists a database of protocols with prescriptions for diagnostic and therapeutic conduct. The goal attained with GNs is: solution for the admission and servicing of patients at the ICU in a dynamically changing situation at any moment of the night and day.*
*The dynamic workflow model in ICU in the form of a GNs is an adequate approach for optimum distribution of the resources and optimum conduct in the care for patients with severe disorders of the vital functions.*

***Keywords:*** *Intensive care unit, Generalized nets, Dynamic model*

## Introduction

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.

ICU accepts mainly patients in critical condition with disturbed vital functions. The immediate intervention of a highly-trained health care team is of crucial importance, since time may be critical. Therefore, optimization procedures turn out expedient [3, 4, 5].

There is a multitude of processes, each of different complexity, that flow in parallel at every moment in an ICU. Their organization with respect to time and work load should be planned in the best possible (including time-saving) way. This motivates the need for appropriate formalization of the activities and the relationships between them. To that end, our approach is to use the theory of GNs.

## The method

### *Formal background on GNs*

Generalized Nets [1, 6] are extensions of the Petri nets and other modifications of them. They are tools intended for detailed modeling of parallel processes.

A GNs can be viewed as a collection of ***transitions***, defined in turn as sequences of ***places***. Transitions are the basic building blocks of GNs. Every transition is assigned an index matrix whose elements are predicates evaluated against two of the places – an input and an output one. Such matrices are called ***transition conditions***. The places contain dots called ***tokens*** – dynamical elements entering the net with initial characteristics and get additional characteristics while traveling within the GNs. Tokens proceed from the input to the output places of the transitions if the transition condition predicates corresponding to the input places (containing tokens) and output places (where the tokens would go to) are evaluated as “true”. Otherwise, if the transition condition predicates are evaluated as “false”, the tokens remain in the input places of a transition. GNs tokens are discernible – every token has its own identifier and gains its own history that could influence the development of the whole process modeled by the GNs.

Two time-moments are specified for a GNs: startup and termination of functioning, respectively.

A GNs has the following components:

- Static structure: determined by the input and output places of the net, as well as the index matrices of the arcs and the transition capacities.
- Dynamic structure: determined by the GNs tokens and the transition conditions.
- Temporal components: activation moment, elementary time-step of the fixed time scale, duration of the net functioning, transition activation moments and duration of their active state;
- Memory of the net.

The workflow represented by means of GNs is based on assumptions characteristic of ICU.

### *The ICU workflow*

*Assumptions:* i) incoming patients have different degrees of malfunction of one or more vital functions; ii) each function is assigned a weight to reflect its relative importance. Using this grading, patient service can be prioritized [7]. ICU patients are of unstable physical condition and have often multi-systemic problems. These features increase the susceptibility to errors and taking inappropriate measures; iii) each doctor and nurse in the unit has a certain qualification; iv) at every moment, they also have a specific work load determined by the need to care of particular patients; v) the unit’s equipment capacity is limited; vi) there exists a formal hierarchy within the staff respected in decision making.

The goal of the workflow organization in an ICU is to assign a medical team to every patient in such a way that the team’s qualifications match the patient’s condition best. Problems arise if the work load limit of the specialists is exceeded. In these cases, it may be necessary to make concessions as concerns the correspondence between the team’s qualifications and the patient’s condition. These may lead to a certain risk.

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 functioning of the system starts with the choice of medical team and equipment of the patient's treatment. Initial assessment of the patient's condition is performed under the hierarchy. The decisions are as well made by the leading specialist available. The head of the unit or the department allocates a bed to the patient basing on the data on bed occupancy. At this level, a health care team (consisting of a doctor and a nurse) should also be assigned. To this end, the staff database is used (it provides data on their qualifications and current work load). Initially, the choice is made on the basis of the correspondence between the patient's condition and the qualifications of the staff. Next, the staff availability is checked to make sure the workload does not exceed the specified limits. This is also the limit to the patient acceptance capability – when the available personnel are unable to accept more. When the maximum load of a suitably qualified specialist is reached, another one is selected basing on specified criteria until the load check succeeds. The same is done to assign nurses, until the final choice is ready. If necessary, this procedure is performed by the doctor on duty. At the next stage, the necessary equipment, consumables etc. needed for the patient are determined.

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 application of GNs is aimed at:

- finding an optimal solution for accepting and caring of patients at an ICU at any time of the day under fast-changing conditions
- determining the potential risk for the patient when the care needs to be reduced.

## Results

The developed GNs-model describes a particular intensive care clinic. It comprises 9 transitions which represent the following: a patient's entering and initial assessment of his/her condition ($Z_1$), available equipment as well as consumables ($Z_2$), unit state ($Z_3$), head of unit ($Z_4$), head of department ($Z_5$), doctors ($Z_6$), nurses ($Z_7$), state of the patient after his enterence ($Z_9$). There are internal and external tokens in the model. The former reflect the entering and leaving of patients, as well as acquisition of patient information. The latter ones are related to decision-making procedures of allocating a bed, assignment of health care team, requests of materials and medicaments, taking the necessary measures.

A patient entering the unit is represented by an α-token in place $l_0$. This token has as its initial characteristic information on patient's current state. Two more tokens can appear at the input of this transition: β- a database containing information on previous treatments and γ-protocols with recommendations for specific actions. The α-token splits into several new tokens that proceed on to the decision-making transitions.

The process of assigning a health care team is carried out stepwise by strictly respecting the hierarchy. In place $l_{10}$ of transition $Z_3$ there is a token δ, which characteristic is the database of the clinic. It is designed to store information on the bed occupancy and patients condition, health care teams, used and necessary materials, performed manipulations. Following the hierarchy, transitions $Z_4$ to $Z_7$ are passed consecutively. At the end of this procedure, decisions are made on assigning a bed and a health care team (a doctor and a nurse) to the patient, as well as the necessary equipment, consumables etc. Transition $Z_9$ represents the process of achieving a stable state of the patient. Its output place $l_{34}$ reflects a patient's discharge from the clinic for some of the possible reasons.

The model's transitions are described as follows:

$Z_1 = <\{l_0, l_1, l_2\}, \{l_3, l_4, l_5,\}, t_1', t_1'',$

| | $l_3$ | $l_4$ | $l_5$ |
|---|---|---|---|
| $l_0$ | true | true | true |
| $l_1$ | $W_1$ | $W_1$ | $W_1$ |
| $l_2$ | true | true | true |

$, l_0 >$, where:

$W_1$ = "information from elsewhere is available on past disorders in the condition of the accepted patient".

At this stage, assessment is made of the patient's condition. The damaged functions and the severity are estimated. If available, an external database with information on the patient is consulted. The initial measures to take are determined according to the specific case recommendations.

$Z_2 = <\{l_4, l_8, l_{11}, l_{18}, l_{24}, l_{33}\}, \{l_6, l_7, l_8\}, t_2', t_2'',$

| | $l_6$ | $l_7$ | $l_8$ |
|---|---|---|---|
| $l_4$ | true | false | true |
| $l_8$ | false | $W_1$ | true |
| $l_{11}$ | false | false | true |
| $l_{18}$ | false | false | true |
| $l_{24}$ | false | false | true |
| $l_{33}$ | false | false | true |

$, \vee (l_4, l_8, l_{11}, l_{18}, l_{24}, l_{33}) >$, where:

$W_1$ = "the clinic requests information on the availability of necessary materials and medicaments".

The transition from an input to an output place would only be possible if the corresponding predicate becomes "true":

$Z_3 = <\{l_5, l_7, l_{10}, l_{16}, l_{22}, l_{27}, l_{30}, l_{35}\}, \{l_9, l_{10}\}, t_3', t_3'',$

| | $l_9$ | $l_{10}$ |
|---|---|---|
| $l_5$ | true | true |
| $l_7$ | false | true |
| $l_{10}$ | $W_1$ | true |
| $l_{16}$ | false | true |
| $l_{22}$ | false | true |
| $l_{27}$ | false | true |
| $l_{30}$ | false | true |
| $l_{35}$ | false | true |

, v ($l_5$, $l_7$, $l_{10}$, $l_{16}$, $l_{22}$, $l_{27}$, $l_{30}$, $l_{35}$) >, where:

$W_1$ = "database information on the clinic is requested".

$Z_4$=<{$l_9$, $l_{17}$},{$l_{11}$, $l_{12}$, $l_{13}$, $l_{14}$, $l_{15}$, $l_{16}$, $l_{17}$},$t_4$',$t_4$",

| | $l_{11}$ | $l_{12}$ | $l_{13}$ | $l_{14}$ | $l_{15}$ | $l_{16}$ | $l_{17}$ |
|---|---|---|---|---|---|---|---|
| $l_9$ | false | false | $W_1$ | false | false | false | true |
| $l_{17}$ | $W_2$ | $W_3$ | $W_4$ | $W_5$ | $W_6$ | true | true |

, v ($l_9$, $l_{17}$) >, where:

$W_1$ = "the clinic head is absent or wishes to convey information to a department head";
$W_2$ = "the clinic head requests particular equipment, medicaments, consumables etc.";
$W_3$ = "the clinic head has made a decision on a given patient – health care team, materials and bed allocation";
$W_4$ = "necessity of transferring the responsibility for the decision to the head of the department";
$W_5$ = "necessity of announcing a particular decision before the specialist staff";
$W_6$ = "necessity of announcing a particular decision before the nurse staff".

$Z_5$=<{$l_{13}$, $l_{23}$},{$l_{18}$, $l_{19}$, $l_{20}$, $l_{21}$, $l_{22}$, $l_{23}$},$t_5$',$t_5$",

| | $l_{18}$ | $l_{19}$ | $l_{20}$ | $l_{21}$ | $l_{22}$ | $l_{23}$ |
|---|---|---|---|---|---|---|
| $l_{13}$ | false | false | $W_1$ | false | false | true |
| $l_{23}$ | $W_2$ | $W_3$ | $W_4$ | $W_5$ | true | true |

, v ($l_{13}$, $l_{23}$) >, where:

$W_1$ = "the head of the department is absent";
$W_2$ = "the head of the department requests particular equipment, medicaments, consumables etc.";
$W_3$ = "the head of the department has made a decision on a given patient – health care team, materials and bed allocation";
$W_4$ = "necessity of transferring the responsibility for the decision to the doctor on duty or announcing a particular decision before the physician";
$W_5$ = "necessity of announcing a particular decision before the nurse staff";

$Z_6$=<{$l_{14}$, $l_{20}$, $l_{28}$},{$l_{24}$, $l_{25}$, $l_{26}$, $l_{27}$, $l_{28}$},$t_6$',$t_6$",

| | $l_{24}$ | $l_{25}$ | $l_{26}$ | $l_{27}$ | $l_{28}$ |
|---|---|---|---|---|---|
| $l_{14}$ | false | false | false | false | true |
| $l_{20}$ | false | false | false | false | true |
| $l_{28}$ | $W_1$ | $W_2$ | $W_3$ | true | true |

, v ($l_{14}$, $l_{20}$, $l_{28}$) >, where:

$W_1$ = "in charge physician requests particular equipment, medicaments, consumables etc.";
$W_2$ = "in charge physician has made a decision on a given patient – health care team, materials and bed allocation";
$W_3$ = "in charge physician should assign a nurse for the patient";

$Z_7$=<{$l_{15}$, $l_{21}$, $l_{26}$, $l_{31}$},{$l_{29}$, $l_{30}$, $l_{31}$},$t_7$',$t_7$'',

| | $l_{29}$ | $l_{30}$ | $l_{31}$ |
|---|---|---|---|
| $l_{15}$ | false | false | true |
| $l_{21}$ | false | false | true |
| $l_{26}$ | false | false | true |
| $l_{31}$ | true | true | true |

, v ($l_{15}$, $l_{21}$, $l_{26}$, $l_{31}$) >.

$Z_8$=<{$l_{12}$, $l_{19}$, $l_{25}$, $l_{29}$},{ $l_{32}$},$t_8$',$t_8$'',

| | $l_{32}$ |
|---|---|
| $l_{12}$ | true |
| $l_{19}$ | true |
| $l_{25}$ | true |
| $l_{29}$ | true |

, v ($l_{12}$, $l_{19}$, $l_{25}$, $l_{29}$) >.

$Z_9$=<{$l_3$, $l_6$, $l_{32}$, $l_{36}$},{ $l_{33}$, $l_{34}$, $l_{35}$, $l_{36}$},$t_9$',$t_9$'',

| | $l_{33}$ | $l_{34}$ | $l_{35}$ | $l_{36}$ |
|---|---|---|---|---|
| $l_3$ | false | false | false | true |
| $l_6$ | false | false | false | true |
| $l_{32}$ | false | false | false | true |
| $l_{36}$ | $W_1$ | $W_2$ | true | true |

, v ($l_3$, $l_6$, $l_{32}$, $l_{36}$) >, where:

$W_1$= "necessity of more equipment, materials, or medicaments, or of releasing the requested ones";
$W_2$ = "the patient should be discharged".

The GNs-model is presented in Fig. 1.

The model can be used to assist resource and personnel load planning, as well as to locate drawbacks in the organization of the unit. The capacity of the clinic is determined by bed facilities, staff load, and the available equipment. The model can immediately show if it is possible to accept a new patient, or other ICU should be sought. Refusal to accept a patient could only happen if (1) no bed is available and the condition of the patients does not allow for a discharge; (2) there is no sufficient equipment to care for the patient and sustain stability in his/her condition. Such situations should be reduced as much as possible. The present model could be used to determine the optimum level of staff and equipment.

The achievement of a sustained stable state of the patient usually requires trade-offs. These may be the cause of a certain risk. It depends on the severity of the body malfunctions, the degree to which the latter match the qualification of the doctors, the work load of the specialists. The basic goal is risk reduction.

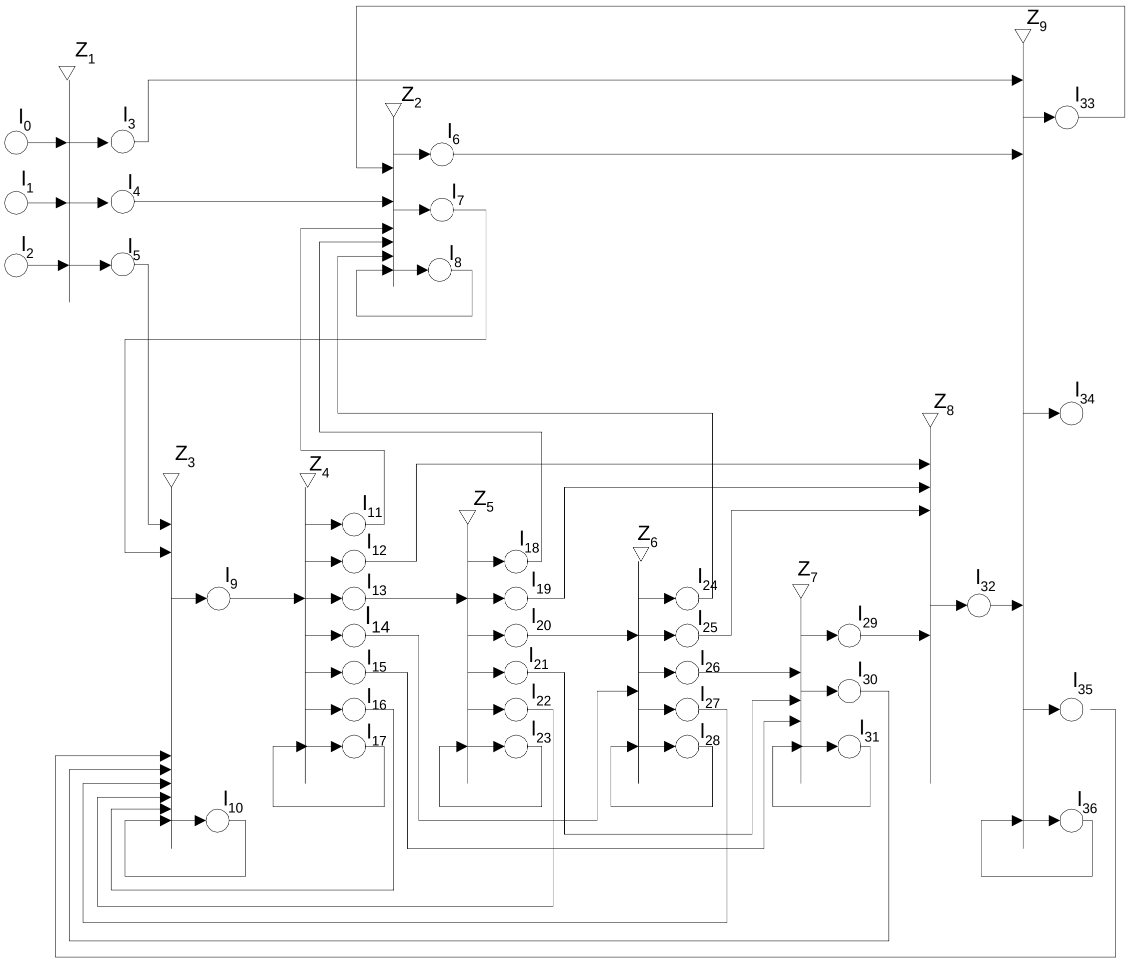


Fig.1 A GNs-model of the work flows in an ICU

The risk can be determined – to that end, the theory of intuitionistic fuzzy sets (IFS) can be used [2]. This direction of research is envisaged as a further work. In order to determine the state, we plan to use degrees of certainty and uncertainty (basic elements of IFS). Thus the risk for a patient with a particular procedure would be described more precisely.

## Conclusion

Technology advances and introduction of modern approaches to intensive treatment could reduce significantly the degree of uncertainty regarding the patients' condition. Such a new environment would contribute to a smaller amount of subjective errors.

The GNs-based workflow model of an ICU is a tool suitable for optimum distribution of resources and care of patients with serious disturbances of their vital functions. It is capable of assisting the monitoring of bed occupancy, patients' condition, assigned medical teams, available, necessary, and used consumables and equipment. Using these, forecasts could also be produced on the outcome of treatment.

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