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Computer simulation of a medical diagnosing support process

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Abstract. The paper presents the computer method of simulation for the process of determining the initial medical diagnosis and the method of examining the selected qualitative characteristics of obtained diagnoses. The presented Computer Medical Decisions Support System uses diagnostic conclusion method based on defining a similarity between the patient's condition and diseases' patterns contained in repository. The application allows simulation of the diagnostic process and examination of qualitative characteristics of this process, particularly: a reliability indicator of generated medical diagnosis with different test scenarios is presented. This computer program was built using .NET Framework technology and supporting libraries.
Keywords: clinical decision support system, disease symptoms, risk factors, initial diagnosis, diagnosis reliability, multicriteria optimization, similarity indicators, similarity relations, pattern recognition

1. Introduction

The main objective of this study was to develop the computer method of simulation for the process of determining an initial medical diagnosis and the method of examining the qualitative characteristics of the medical diagnosing support process. An initial medical diagnosis is determined on the basis of identified disease symptoms and risk factors and their degree of intensity [8, 9, 10, 13].

This study presents an algorithm for diagnostic inference supporting, based on the idea of comparing the obtained patient's results with the disease unit patterns contained in a medical repository of diagnosing system. The result of a matching process is a set of images of probable diseases in two-criterial diagnostic space.

The accepted criterion for assessing the degree of proximity (similarity) of the patient' health image to disease indicator patterns is based on the function forms defining partial distances in the terms of found diseases symptoms and risk factors. The paper presents a definition of the degree of diagnostic reliability, defining by the diagnosing algorithm and the definition so-called in formativeness of patient's medical examination results.

The main result of this work is the method for simulation of the medical diagnosing support process and for studying the diagnostic reliability of the algorithm and its many other characteristics. The simulation process consists of generating the collection of disease unit patterns according to a certain standard and sets of medical examination results and then simulating the diagnosing process.

The result of each simulation cycle is to determine the collection of potential medical diagnosis and necessary qualitative characteristics of the diagnostic process (including diagnostic reliability). The developed method of a study additionally allows us to determine such characteristics of the diagnostic process as: diagnosis ambiguity indicator, diagnosis sharpness indicator, and to examine the sensitivity of the algorithm to errors in determining medical examination results.

The obtained (as a result of the supporting algorithm) set of diagnoses that are the most probable, together with the determined diagnostic reliability degree may give rise to the decision by a doctor about any further specialized examinations of the patient.

This study also presents the description of the application's structure and operation which allows to make an initial medical diagnosis depending on recognized disease symptoms, risk factors, and expert medical knowledge in the disease diagnostic [11, 12, 13, 14]. The applied diagnostic algorithm bases on the idea of measuring the distance between the patient's health state model and appropriate defined patterns of disease units [1, 7].

2. Two-criteria diagnostic model

The decision task of choosing the optimal diagnosis can be defined as follows:

$$\left(\mathrm{M}_o(x), d(x,m)\overline{R}\right), \tag{2.1}$$

where: $\mathrm{M}_o(x) \subset \mathrm{M}$ — initial estimation of the set of possible diagnosis's (M — repository) for the patient $x \in X$ [10];
$d(x,m) = \left(d_1(x,m), d_2(x,m)\right)$ — two-criteria assessment of "similarity degree" [9, 10] of the patient's health state $x \in X$ to the disease pattern image $m \in \mathrm{M}_o$;

$d(x, m)$ — denotes the distance of the patient's condition x (resulting from occurring symptoms) from the pattern of disease, defined on the basis of medical symptoms and similarly denotes the distance of the patient x, (resulting of risk factors) from the pattern of disease, defined on the basis of risk factors;
$\overline{R}$ — diagnostic preferences model (called the similarity relation) [3, 4, 5, 6, 7, 9, 10].

The diagnostic preference models that are most frequently considered [3, 10] are:
- Pareto model,
- hierarchical model (1, 2),
- hierarchical model (2, 1),
- pessimist model (optimist),
- collective model (consilium model).

The relation of diagnostic similarities $\overline{R} \subset \mathrm{M} \times \mathrm{M}$ [10] in the general case gives the opportunity to organize a set of potential diagnoses in the context of "similarity" of the patient's health status model $f(x)$ [4] to the patterns of specific diseases from the set in the repository M. The fact that $(\overline{m}, m) \in \overline{R}$ means that the disease pattern $\overline{m} \in \mathrm{M}$ is more "similar" (more probable) to the $f(x)$ model of the patient's health condition $x \in X$ than the disease pattern $m \in \mathrm{M}$. We can interpret it as $\overline{m}$ disease is "more likely" than the disease m with currently identified symptoms and risk factors [8, 10].

Optimization model (2.1) means that the similarity of "the patient's health condition" to the disease $\underline{m}$ is greater than to the disease m, both in the context of observed symptoms and risk factors

$$\overline{R} = \left\{ (\overline{m}, m) \in \mathrm{M} \times \mathrm{M} \,\middle|\, d(x, \overline{m}) \le d(x, m) \right\}. \tag{2.2}$$

By having the so-called evaluation image of the set Y of the initial estimate $\mathrm{M}_o(x)$ [10], a problem (2.1) can be written in a simple form:

$$(Y, R), \tag{2.3}$$

where:

$$Y = d\left(M_o(x)\right) = \left\{ \begin{matrix} \left(y_1^m, y_2^m\right) \in R^2 \,\middle|\, y_1^m = d_1(x, m), y_2^m = \\ = d_2(x, m), m \in M_o(x) \end{matrix} \right\}. \tag{2.4}$$

The relation R is a diagnostic similarity model analogically, as (2.2)

$$R = \{(y,z) \in \mathsf{R}^2 \ x \ \mathsf{R}^2 \,|\, y \le z\}. \tag{2.5}$$

It is a reflexive relation, non-symmetric and transitive — i.e. an order relation [3, 10]. This type of diagnostic preference is called the Pareto model. The solution to the problem (2.3) of determining the "optimal diagnosis" is the so-called dominating or non-dominating solution [3, 10]. From relations' properties (2.5) it results that if the dominating solution exists then it is unique and it is also a non-dominating solution. Therefore, a solution to a problem (2.3), having a practical solution, is a non-dominating solution [3].

A set of the non-dominating solutions Y_R^N of the problem (Y, R) is defined as follows:

$$Y_N^R = \{\, y \in Y | \text{ does not exist } z \in Y - \{\, y\},\ \text{that}\,(z,y) \in R\}. \tag{2.6}$$

The opposite image (counter image) [3, 10] of the set Y_N^R, in the set of initial estimations diagnosis's of $\mathrm{M}_o(x)$, is the "non-dominating diagnosis" set M_N^R.

$$\mathrm{M}_N^R = F^{-1}(Y_N^R) = \left\{ \overset{o}{m} \in \mathrm{M}_o(x) \middle| d(x,\overset{o}{m}) \in Y_N^R \right\}, \tag{2.7}$$

It is "a collection of diseases from which none more similar exists in the repository" to the patient's health condition model, with identified symptoms and risk factors.

In other words, in the evaluation space $d(\mathrm{M}_o)$ of images of disease patterns there are no images "closer" to the $f(x)$ model of the patient's health condition $x \in X$ than the images of diseases found in the set Y_N^R.

The ranking of diagnosis's proposed in [8, 10], based on the so-called ideal point [3], allows us to determine "the closest diagnosis", i.e. "the most probable diagnosis".

From the general properties of the multicriteria optimization problem it results that with the current assumptions in the model, the diagnosis has a property that nothing better exists in the repository M, since it is the best one.

In the process of diagnosing, as noted earlier, other multicriteria mechanisms can also be used resulting from the adoption of models such as the model of hierarchical preferences, pessimistic (optimistic) or collective model.

When using the hierarchical model in the process of diagnosis two cases may occur:

— disease symptoms are more important than risk factors,
— risk factors are more important than the disease symptoms.

Apart from the opinion of medical experts (the first variant predominates) in the calculation process it does not matter, because according to the properties of the multicriteria optimization problem [3, 10] the final result in both cases is included in the M_N^R set (in the Pareto model) and it is a subject to the ranking in accordance with general principles.

The optimist (pessimist) model as well as the collective (consultation) model was not studied as a part of the design work. General properties obtained with these diagnostic result assumptions can be found in [3, 15].

3. Multicriteria properties of characteristics of the diagnostic process

The main result of the implementation of the algorithm determining the initial medical diagnosis is a set of diagnoses that are the most probable, as well as their ranking [3, 10]. The credibility of the essential diagnostic procedure and therefore the outcome is a function of many factors, among others, such as the "content" of the set M (cardinality patterns of diseases) and individual characteristics of the patient. The patient's individual properties determine the subjective sensing of the presence and severity of disease symptoms which in turn affect the so-called "diagnostic information" of patient test results.

From the standpoint of computer support significance in the process of diagnosis, information about the degree of reliability of results is particularly important.

The algorithm is designed, so that regardless of the "information quality" of the obtained patient test results and regardless of the repository content (a set of disease patterns) it leads to the result in the form of a Pareto set and its ranking. However, if there is no disease pattern in the set M for the patient's disease, then determining his/her diagnosis is not possible.

In addition to the diagnosis, information is important about the degree of credibility of the whole procedure as well as "information importance" of the results obtained from the patient. This information and many other characteristics can be obtained by analyzing the results of the computer support. Testing the computer application algorithm [10] fully confirmed such a possibility. Adequate "calibration" of the model and algorithm allow us to qualify the results obtained on the basis of, for example, degrees of diagnosis reliability. The subset location of remote images of the initial diagnosis of the estimation of $d\left(\mathrm{M}_o(x)\right)$ highly depends on the information quality of test results (as far as they are reliable) and on the numbers in the set M containing the repository of disease patterns. The element that characterizes the location of this set is so-called the ideal point $\underset{*}{y}(y)$, which is the greatest lower limit of the subset $d\left(\mathrm{M}_o(x)\right)$ with the adopted model of the similarity relation R (2.3).

Its distance from the virtual pattern image of the disease (that is, from point (0,0)) most probably is a measure of reliability of the obtained result. The symbol $w \in (x, \mathrm{M})$ denotes the degree of reliability of the obtained diagnosis on the basis of the results of $f(x)$ [8], the patient $x \in X$ and the number of disease patterns in the repository, represented by the set M

$$w(x,\mathrm{M}) = 1 - q\left((0,0)\overset{*}{y}(x)\right) = 1 - \left\|\overset{*}{y}(x)\right\|_p, \quad p \geq 1. \tag{3.1}$$

The role of the parameter p in determining the precise form of the standard (3.1) is discussed thoroughly in [3, 15]. In practice, we use $p = 2$ most frequently.

Figure 1 shows two diagnostic situations obtained from the algorithm's runs with the same repository M and different sets of patient test results (patient $x \in X$ and patient $\overline{x} \in X$ [8, 10]). The diagnostic similarity space, in which the location of images of diseases is studied, obtained from the patients' tests is normalized to [0.1] × [0.1]. Depending on the test results (more "expressive" or less "expressive") for each patient, it receives the appropriate "focus" points. They create certain characteristic separate subsets.

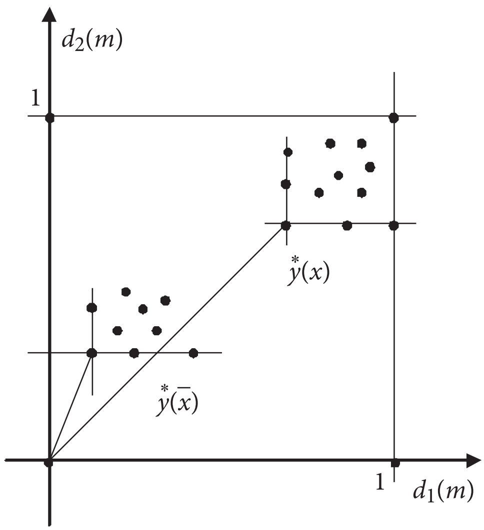

Fig. 1. Diagnostic similarity space

4. Implementation

The simulator application was written on the base of Microsoft .NET Framework technology. In the process of the implementation, C# language was applied. Microsoft Visual Studio 2010 is the project workspace in which the software was prepared.

The repository for the simulator is generated dynamically (when defining relevant parameters specified by the user). It is also possible to use MSSQL database to collect data concerning diseases and to use it in the simulation process.

The software is in the form of windowing application that uses the Windows Forms graphical interface. In order to use the application, it is required to install .Net Framework version 3 or the higher version. The results of each simulation are illustrated thanks to using additional Microsoft Charts library that allows us to generate different types of charts dynamically. The simplified architecture of the application is presented on the below shown picture. We can distinguish here 5 key modules (components) of the proposed application architecture:

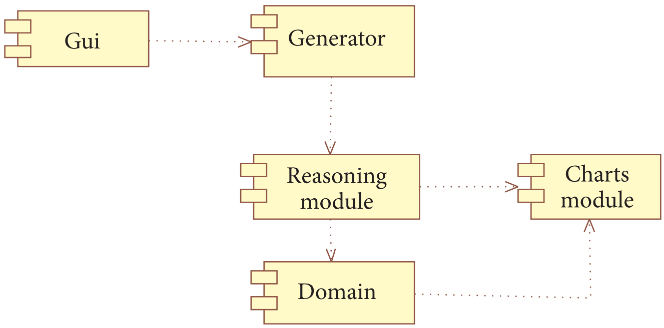

Fig. 2. Application architecture

where: GUI — graphical user interface (Windows Forms);
Generator — component which is responsible for generating test data for simulation; depending on a chosen scenario, the proper data are generated;
Reasoning module — the component which is responsible for performing distance calculations based on previously presented algorithm;
Domain — component which is responsible for illustrating the result of the simulation as two-dimensional charts.

The application window is divided into three panels:

- patient's panel,
- repository panel,
- scenario of simulation configuration panel.

In the patient's panel, the parameters which concern recognized diseases' symptoms and discovered risk factors are defined. The number of each of them cannot be greater than their number in repository. Patient's panel plays a very important role in generating and realizing many of simulation scenarios. It allows us to investigate sensitivity of diagnoses generated by a system, depending on patient's health parameters' changes, in particular intensity level of occurrence of diseases' symptoms and risk factors and number of symptoms' changes recognized in the patient. Also

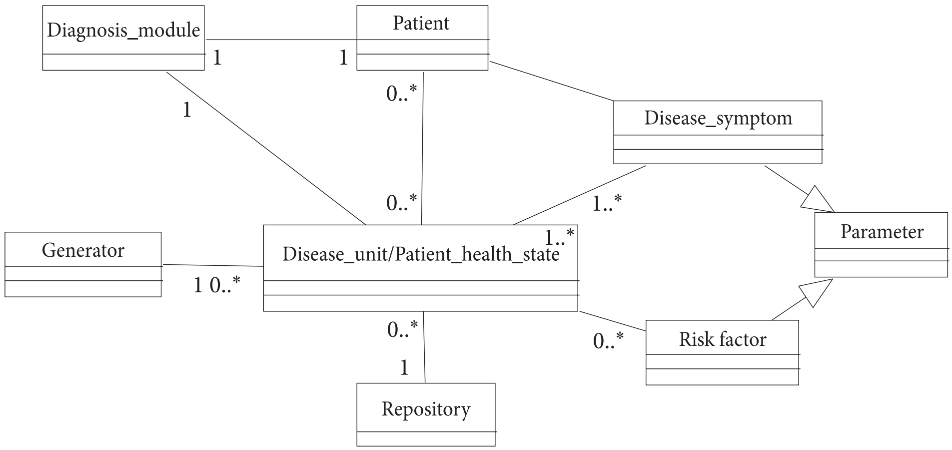

Fig. 3. Simplified simulator application class diagram

Fig. 4. Patient's panel

very important functionality is the possibility of qualitative characteristic analyzing in a situation when many symptoms suggest coexisting diseases occurence.

Repository panel contains a lot of editable controls, though simulation parameters related with the repository can be defined (number of diseases in repository, maximum number of diseases' symptoms and risk factors, etc.). The availability of individual editing controls depends on the chosen simulation scenario.

Simulation panel allows us to choose one of four types of simulation:

Currently, the following simulation scenarios are available:

— Simulation 1: proceeds with constant, unchanging parameters (appropriate calculations are performed only once for the entered parameters),
— Simulation 2: runs with a variable number of diseases in repository (the number of diseases is determined by a value of parameter),
— Simulation 3: proceeds with a variable number of diseases' symptoms and risk factors recognized in patient, and constant number of diseases' patterns contained in repository. At the beginning of the simulation, the quantity of the diagnosed diseases' symptoms and risk factors collection equals 1 and it is being increased during the simulation run until the quantity of the individual collections determined by a user is gained,
— Simulation 4: runs at changing values of intensity factors related to diseases' symptoms and risk factors.

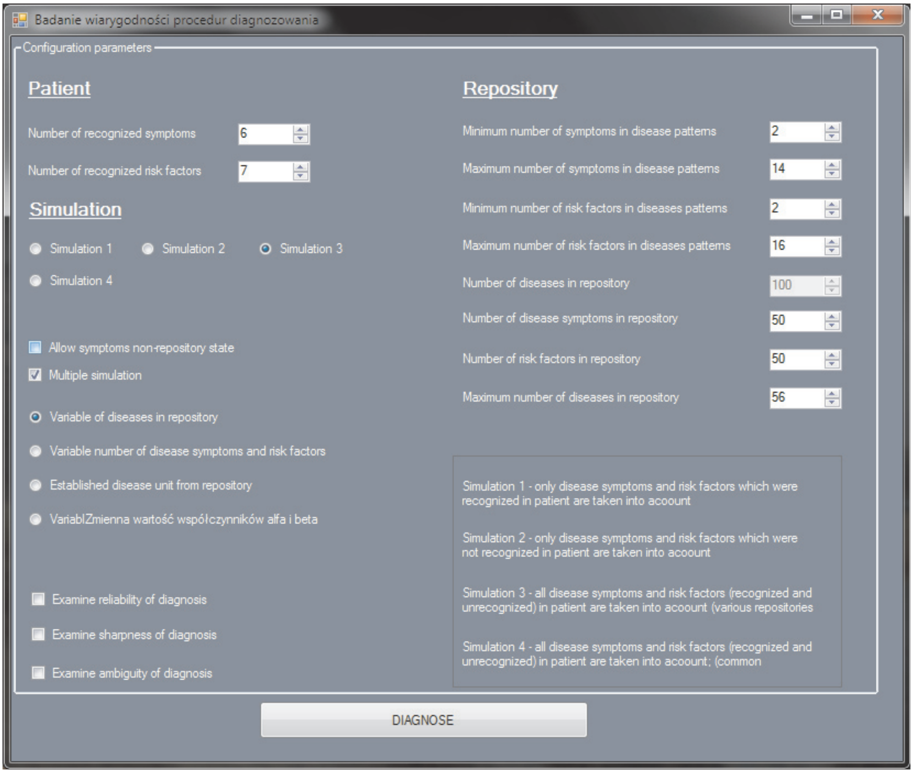

Fig. 5. User Interface

Within each of the above pointed simulations, it is possible to examine the following indicators:

— reliability indicator,
— sharpness indicator,
— ambiguous indicator.

After the simulation is finished, the charts presenting the obtained results are generated.

Each of disease (especially its image of similarity to a patient's health state) is presented in the charts as a red point. There are no diseases with a higher probability of occurring than the ones indicated with green colour (front of Pareto set) according to an implemented diagnosing method. Blue point (the utopian point) is the point determined after taking into account:

— the minimal distance of patient's health state to a disease pattern related to diseases' symptoms in the whole repository,
— the minimal distance state of patient's health to disease pattern related to risk factors in the whole repository.

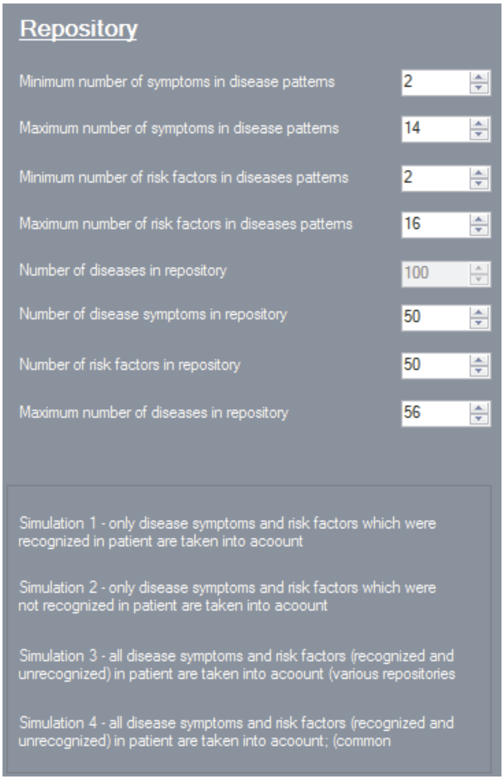

Fig. 6. Repository panel

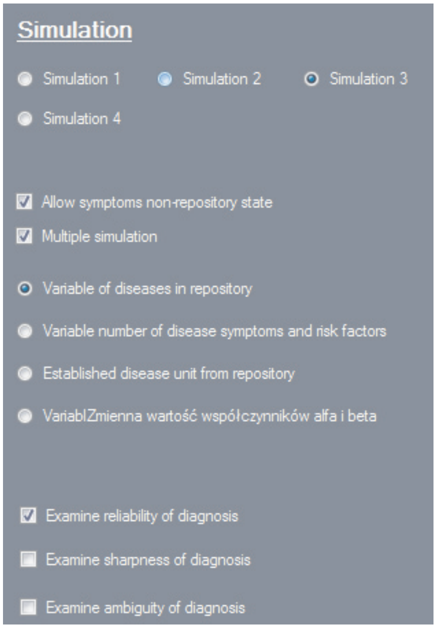

Fig. 7. Panel of simulation configuration

This is the image of an ideal similarity of patient's health state to an ideally matching utopian disease which unfortunately is outside from the repository.

Green points of the chart set the front of the Pareto collection. The user is allowed to define in which phases of simulation the charts with results are generated (how many of them should be generated). There is also the possibility to save results to a text file. The number (name) of disease entity represented on the chart by specified point can be obtained by clicking on it with the cursor.

An especially important indicator, which is investigated in the simulation process is diagnostic reliability described by formula (3.1).

In the considered example, the value of p parameter equals 2 (geometric distance) [3]. As it is shown in the formula, the value of the diagnostic reliability indicator is strongly dependent on the utopian point location. As in the case where the possibility of disease occurrence was examined, here we also obtain the chart illustrating the change of the presented indicator. It can be examined in all chosen simulation scenarios.

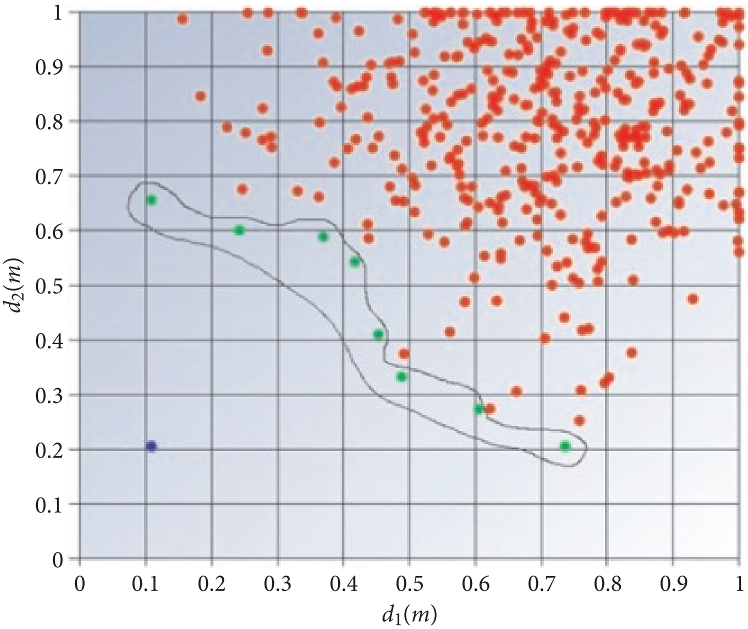

Fig. 8. Determining the set of diagnoses that are the most probable

5. Examples of simulation runs

The presented simulator allows us also to examine many of other qualitative characteristics of the obtained diagnoses including sensitivity of generated diagnoses to the changes of information level in medical results. It allows us to designate threshold of results information level and thus supporting procedure calibration. Below it will be presented exemplary simulation process for scenario with variable number of diseases in repository. The simulation calculations used a virtual test data. The number of diseases' symptoms and risk factors recognized in patient remains the same. Except the observation of charts showing changes in the Pareto collection (for diseases with the highest probability of occurring), we need also to generate a "reliability indicator" value chart.

After selecting the appropriate fields in the application, we will define the multiplicity of collections for disease symptoms and risk factors recognized in a patient. In this example, the parameter values were chosen as follows:

Parametr	Value
Number of recognized symptoms	32
Number of recognized risk factors	4
Minimum number of symptoms that describes the pattern of disease	2

Maximum number of symptoms that describes the pattern of disease	8
Minimum number of risk factors that describes the pattern of disease	2
Maximum number of risk factors that describes the pattern of disease	6
Number of symptoms in repository	110
Number of risk factors in repository	70
Maximum number of diseases in repository	400

During the simulation, the application generated a chart showing the patient's health state distance from individual diseases in repository. Charts were created for every 50 disease patterns added to repository. The study presents selectively only a part of the beginning, the middle and the end of the simulation. The above charts present the generated similarity spaces that are the images of the current content of repository in comparison with the patient's health state recognized by the doctor (the collection of recognized diseases' symptoms and risk factors and their intensity degrees). An important observation is that the inverse images of some points, determined in the disease space, can be the collections with the multiplicity greater than 1.

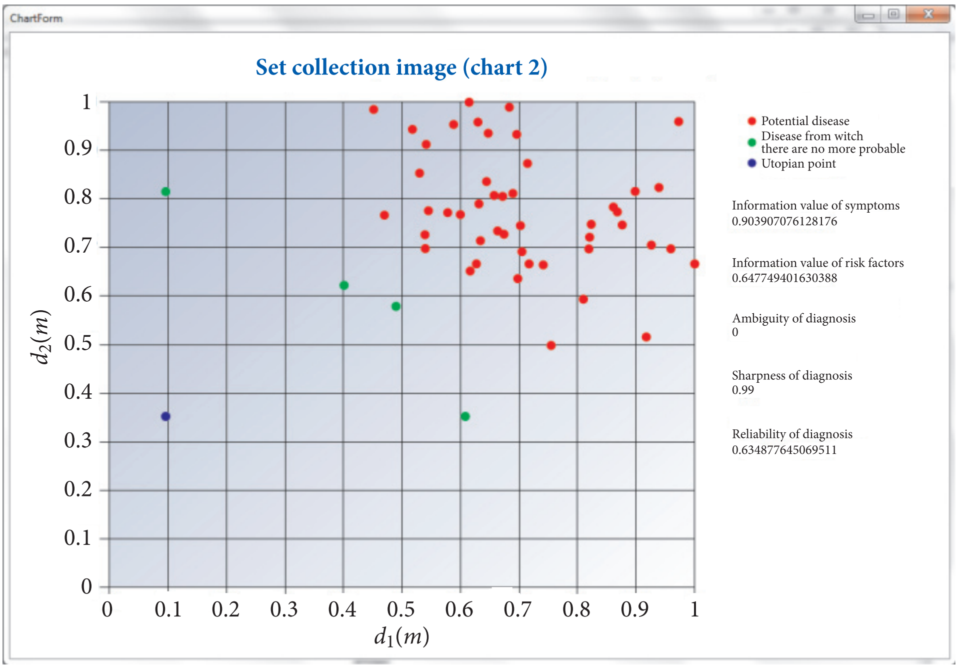

Fig. 9. Repository — 50 diseases

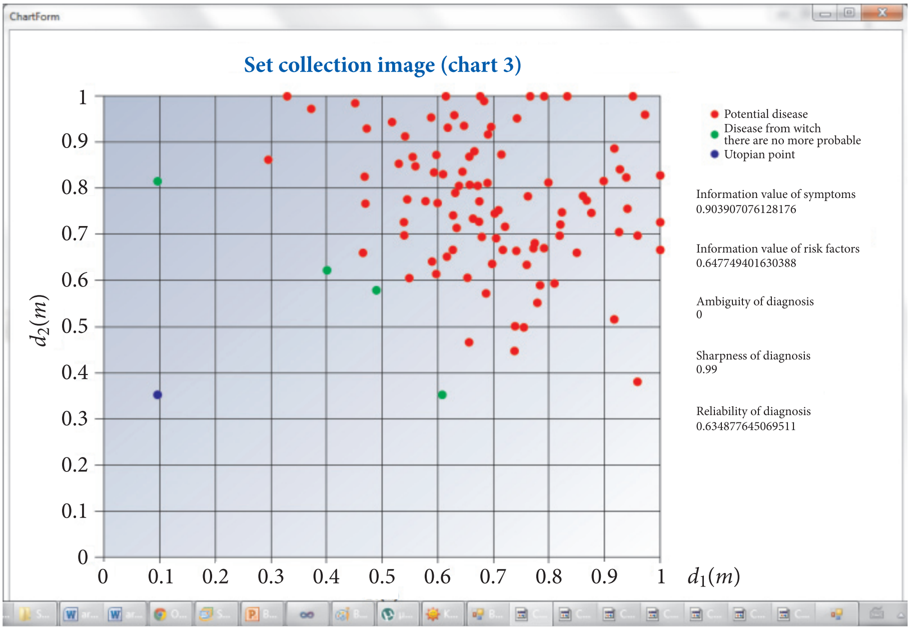

Fig. 10. Repository — 100 diseases

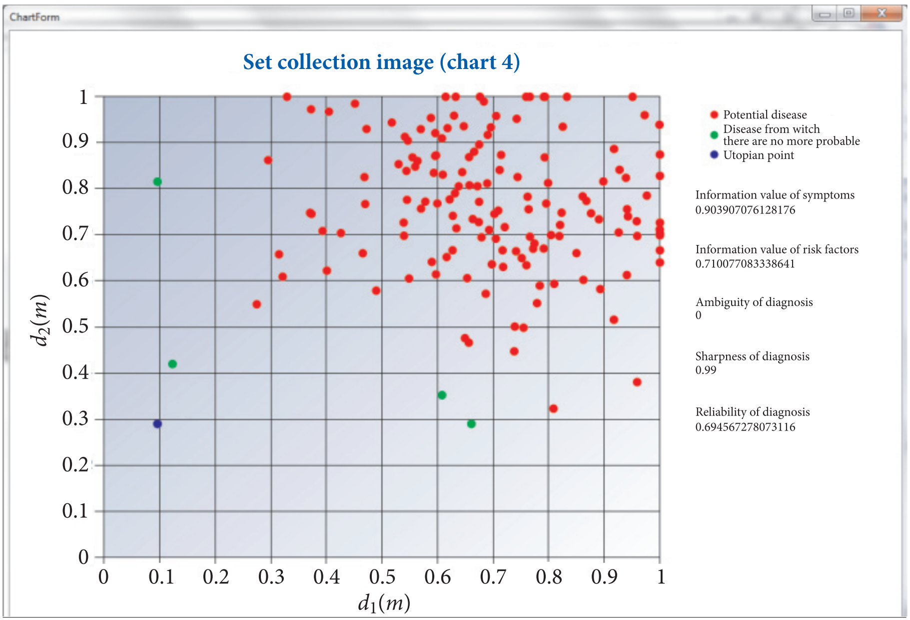

Fig. 11. Repository — 150 diseases

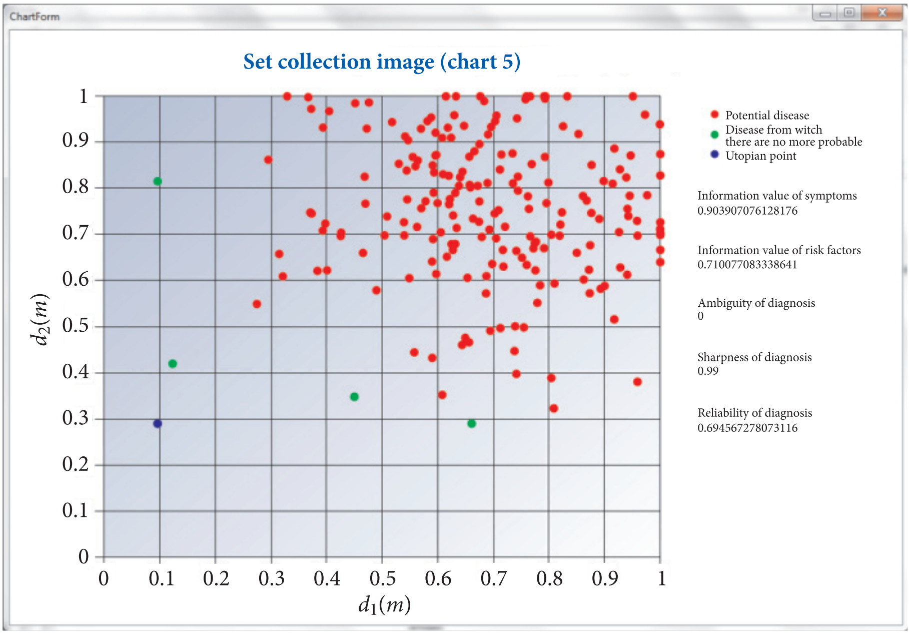

Fig. 12. Repository — 200 diseases

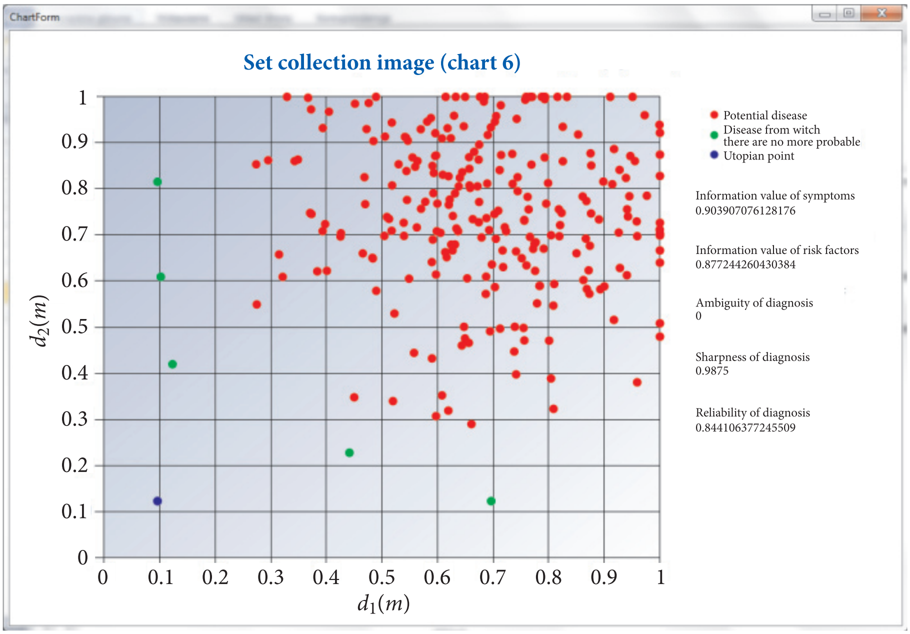

Fig. 13. Repository — 250 diseases

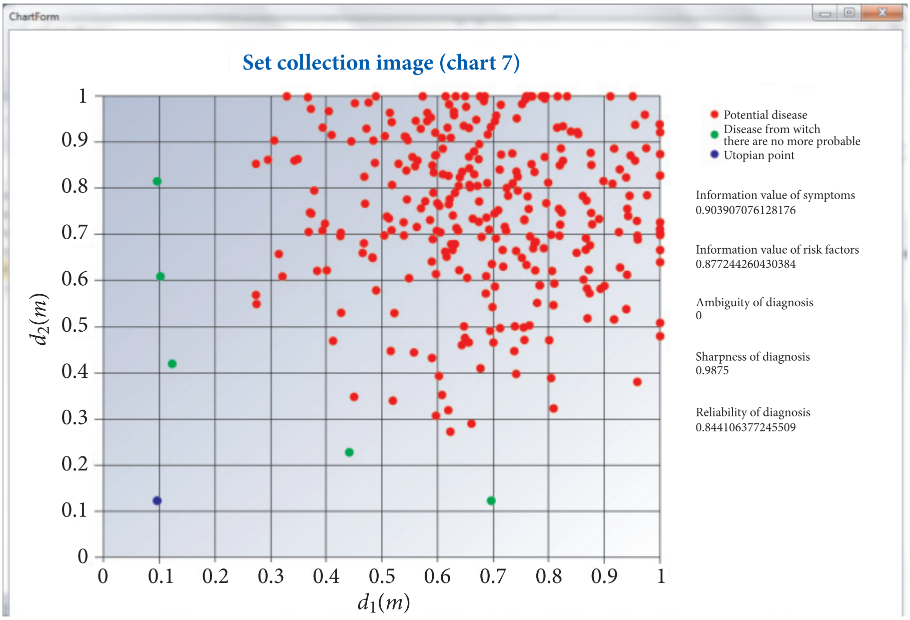

Fig. 14. Repository — 300 diseases

Figures numbered from 9 to 14 show consecutive similarity images of the patient's health state determined by the doctor on the basis of identified disease symptoms and risk factors to disease patterns "expanding" in terms of the number of contained disease unit patterns of repository. Interesting is the evolution of so-called Pareto front showing the images of disease units with the highest probability of occurring.

The phase of initial diagnosis is particularly important in the procedure of recognizing the disease. The use of specialized tools based on medical knowledge supports the process of determining the initial diagnosis. Narrowing the diagnostic process to the certain disease subset has the crucial impact on the strategy of further specialized examinations and the patient's treatment path.

The software supporting the process of determining the initial medical diagnosis contributes to minimizing the costs and time of examinations and increasing effectiveness of the treatment of the patient as well. The simulator presented in this work allows us to study the basic qualitative characteristics of medical diagnosis generated by the computer medical decision support system. Currently, simulator allows us to study such characteristics as diagnosis reliability, diagnostic clarity, and diagnosis ambiguity. It is planned to develop the tool by adding new simulation scenarios and allowing the study of other qualitative characteristics of the medical diagnostic process.

Particularly important seems to be the possibility of simulative testing of sensitivity of generated diagnoses to informative changes of medical results understood in a broad sense [3, 4]. Another simulator application area, very interesting and important from the practical point of view could be the examination of conditions of so-called "coexisting diseases" occurrence. Such studies allow the determination of so-called thresholds of sensitivity and calibration of all parameters of the adopted model of diagnostic inference.

6. Conclusions

The most important factor determining the quality (effectiveness) of the initial diagnosis is the size (cardinality) of the set M (diseases repository). It results from the fact that the developed algorithm compares the image of the patient's condition only with the patterns of diseases included in the repositoryM.

The application has been designed so that the extension of tables DISEASE and RISK FACTOR OCCURANCE is easy and the data publicly available [9].

The most important properties of the developed algorithm and application are:

— Module replaceability,
— Ability to visualize obtained results,
— Ease of creating rankings,
— Simulation susceptibility,
— Ability to obtain information about coexisting diseases.

Interchangeability of modules is particularly important if you need to use other similarity functions (distance function) [7] and to compare the results obtained in the context of evaluating the effectiveness of the diagnostic process.

The possibility of visualizing the obtained results can be of great practical importance as an additional diagnostic tool for the physicians' family. The graphical representation of a set of potential diagnoses on a computer screen (including a set of the most probable diagnoses) allows the physician to easily assess the "significance (reliability) of the diagnosis". Reliability of the diagnosis is a derivative of the distance between the patterns of "diseases that are the most probable" and the model of the patient's condition. The smaller is this distance, the more reliable is the diagnostic process. Visualization also allows for an initial assessment of the so-called "clarity of diagnosis".

The algorithm allows us to very easily create a ranking of diagnoses (creating a list of diagnoses from the most likely to the least likely ones). The position on the list of diagnoses is also linked to a number specifying the distance from the model of the patient's condition.

Comparison of these numbers brings further evidence as to the clarity of the diagnosis and the possibility of presence of coexisting diseases.

The simulation susceptibility is a very important property of the algorithm, because it facilitates carrying out research on the quality of the diagnostic process. It also gives the possibility of training or testing the diagnostic skills of the physician.

An adequate design of the testing data allows us to quickly test the algorithm's sensitivity to physician's errors during determining the symptoms and risk factors and mainly their degree of intensity.

The algorithm also enables obtaining information on the occurrence of potential coexisting diseases in the model, even though formally such a possibility was not expected. The possibility of coexisting diseases is mainly due to the cardinality of the Pareto set (the greater the cardinality of this set, the greater likelihood of coexisting diseases). The "contents" of the Pareto set define the possible "subsets" of coexisting diseases.

The analysis of the value of the ranking function allows us to determine the potential set of diseases that are "almost as similar" model of the patient's health condition.

The presented results of project works [12, 13] and the properties of diagnostic mechanisms used have been confirmed during tests carried out with the application [11]. The use of multicriteria optimization models in initial diagnosis support algorithms allows, depending on the accepted similarity relation model, determining diagnosis, taking into account disease symptoms and risk factors. The result of the initial diagnosis is the basis for determining the optimal strategy for additional technical research.

The most important properties of multicriteria mechanisms used to support medical decisions in decision nodes of clinical pathways are:

— the possibility of placing the decision support algorithms in decision nodes of clinical paths,
— the guarantee of optimality in terms of Pareto (a set of diagnoses from which there is no other probable in the repository),
— ease in creating a ranking of initial diagnoses,
— ability to visualize the set of diagnoses of initial disease identification,
— replaceability of main algorithm modules (in terms of used patterns, distance function and diagnostic similarity models),
— the possibility to extend the basic model with cases of coexisting diseases,
— susceptibility of a simulation algorithm.

Basic research problems to be included in further work are:

— developing a standard of creating (modeling) patterns of disease entities,
— model extension with a case of "coexisting diseases" — the pattern concept of coexisting diseases,
— determination algorithm based on the initial medical diagnosis of an optimal strategy for additional technical research,
— developing a global three-segment model for determining the final diagnosis (disease symptoms, risk factors, results of specialized tests),

— problem of standardization of medical characteristics obtained from the results of specialized tests.
— Basic practical problems to solve are:
— developing a method for computer diagnostic characteristics interpretability of individual disease entities,
— developing a method for easy automatic expansion of the list of diseases in the repository,
— developing a simple user-friendly interface — the diagnosing physician enters diagnostic data (disease symptoms, risk factors, the results of specialized tests and degrees of severity),
— developing a simple "friendly" visualization module of computer diagnostic decision support results and additional information,
— developing a method for calibrating and testing the model and diagnostic algorithms.

The article is based on the paper presented at the Conference Systems Engineering 2012, Warsaw.

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Komputerowa symulacja procesu wspomagania diagnozowania medycznego

Streszczenie. W pracy przedstawiono metodę komputerowej symulacji procesu wspomagania ustalania wstępnej diagnozy medycznej oraz symulacyjną metodę badania charakterystyk jakościowych procesu diagnozowania medycznego. Przedstawiony Komputerowy System Wspomagania Diagnozowania Medycznego wykorzystuje metodę wnioskowania opartą na określaniu podobieństwa stanu zdrowia pacjenta dozorców jednostek chorobowych zawartych w repozytorium. Przedstawiona aplikacja pozwala na symulację procesu diagnostycznego i badanie cech jakościowych samego procesu w szczególności wiarygodności diagnostycznej generowanych diagnoz medycznych przy różnych scenariuszach badawczych. Program komputerowy wykorzystuje platformę .NET Framework oraz dodatkowe biblioteki.

Słowa kluczowe: system wspomagania decyzji klinicznych, symptomy chorobowe, czynniki ryzyka, diagnoza wstępna, wiarygodność diagnozy, optymalizacja wielokryterialna, wskaźniki podobieństwa, relacje podobieństwa, rozpoznawanie wzorców