



# Novel deep genetic ensemble of classifiers for arrhythmia detection using ECG signals

Paweł Pławiak<sup>1</sup> · U. Rajendra Acharya<sup>2,3,4</sup>

Received: 9 November 2018 / Accepted: 20 December 2018  
© The Author(s) 2019

## Abstract

The heart disease is one of the most serious health problems in today's world. Over 50 million persons have cardiovascular diseases around the world. Our proposed work based on 744 segments of ECG signal is obtained from the MIT-BIH Arrhythmia database (strongly imbalanced data) for one lead (modified lead II), from 29 people. In this work, we have used long-duration (10 s) ECG signal segments (13 times less classifications/analysis). The spectral power density was estimated based on Welch's method and discrete Fourier transform to strengthen the characteristic ECG signal features. Our main contribution is the design of a novel three-layer (48 + 4 + 1) deep genetic ensemble of classifiers (DGEC). Developed method is a hybrid which combines the advantages of: (1) ensemble learning, (2) deep learning, and (3) evolutionary computation. Novel system was developed by the fusion of three normalization types, four Hamming window widths, four classifiers types, stratified tenfold cross-validation, genetic feature (frequency components) selection, layered learning, genetic optimization of classifiers parameters, and new genetic layered training (expert votes selection) to connect classifiers. The developed DGEC system achieved a recognition sensitivity of 94.62% (40 errors/744 classifications), accuracy = 99.37%, specificity = 99.66% with classification time of single sample = 0.8736 (s) in detecting 17 arrhythmia ECG classes. The proposed model can be applied in cloud computing or implemented in mobile devices to evaluate the cardiac health immediately with highest precision.

**Keywords** ECG · Biomedical signal processing and analysis · Machine learning · Genetic algorithms · Ensemble learning · Deep learning

**Electronic supplementary material** The online version of this article (<https://doi.org/10.1007/s00521-018-03980-2>) contains supplementary material, which is available to authorized users.

✉ Paweł Pławiak  
plawiak@pk.edu.pl; plawiak.pawel@gmail.com  
U. Rajendra Acharya  
aru@np.edu.sg

<sup>1</sup> Faculty of Physics, Mathematics and Computer Science, Institute of Telecomputing, Cracow University of Technology, Warszawska 24 st., F-5, 31-155 Kraków, Poland

<sup>2</sup> Department of Electronics and Computer Engineering, Ngee Ann Polytechnic, Clementi 599489, Singapore

<sup>3</sup> Department of Biomedical Engineering, School of Science and Technology, SUSS University, Clementi 599491, Singapore

<sup>4</sup> School of Medicine, Faculty of Health and Medical Sciences, Taylor's University, 47500 Subang Jaya, Malaysia

## 1 Introduction

In the last decades, solving problems from various fields, including medicine, using various machine learning (ML) techniques is very popular [1–6, 9, 46, 50, 53, 54, 57, 58, 60, 61, 75, 76].

This popularity is due to the fact that ML can cope with problems that are difficult to solve in a conventional way due to the unknown rules. Due to the properties of learning and generalization of knowledge, these methods are able to solve many problems. Artificial intelligence techniques achieve high performance in various fields of science. The advantages of ML (in particular, computational intelligence) lie in the properties inherited from their biological counterparts, such as learning and generalization of knowledge (e.g. artificial neural networks), global optimization (e.g. evolutionary algorithms), and use of imprecise terms (e.g. fuzzy systems).

The presented DGEC method draws inspiration from three areas of ML: (1) ensemble learning (EL), (2) deep learning (DL), and (3) evolutionary computation (EC). More information about EL and EC can be found in [51], and about DL in [77].

### 1.1 Heart diseases

Electrocardiography (ECG) is the most popular and the basic technique of diagnosing heart diseases. This is because it is noninvasive, simple and provides valuable information about the functioning of the circulatory system.

Cardiovascular diseases are serious social issue, because of: (a) highest mortality in the world (37% of all deaths, 17.3 million people per year [7, 8, 71]), (b) high incidence, and (c) high costs of treatment (long-lasting and expensive treatment caused by chronic course of the disease [34, 68]). The arguments quoted above will intensify because the number of deaths will grow from 17.3 million (2016) to 23.6 million (2030) [7, 8, 33, 71], which will be caused by the progressive aging of the population.

Current methods for the diagnosing of heart abnormalities are based on the calculation of the dynamic or morphological features of single QRS complexes. This solution is error-prone and difficult because of the variability of these characteristics in different persons [48]. For these reasons, the methods currently presented in the scientific literature do not obtain sufficient performance [23].

The above facts present a strong motivation to conduct research on new methods to support the medical diagnosis early and more effectively diagnose the heart disorders. An important aspect of our research is also to reduce the computational complexity of the developed algorithms in the context of implementing our solution in cloud computing or mobile devices to monitor the health of patients in real time.

### 1.2 Goals

The main goals of this paper are as follows:

- Goal 1 Design new and efficient ensemble (network) of classifiers based on EL, DL, and EC for the automatic classification of cardiac arrhythmias based on segments of ECG signal.
- Goal 2 Design method for patient self-control and prevention application in telemedicine and cloud computing or mobile devices characterized by low computational complexity.
- Goal 3 Design universal method for the general population.

### 1.3 Novelty

Our main novel contribution is:

Deep genetic ensemble of classifiers (DGEC) system consists of three-layer (48 + 4 + 1) ensemble (network) of classifiers made up of: 12 SVM (nu-SVC, RBF), 12 kNN, 12 PNN and 12 RBFNN classifiers + 4 SVM (C-SVC, linear) classifiers + 1 SVM (C-SVC, linear) classifier, based on: three normalization types, four Hamming window widths, four classifier types, stratified tenfold cross-validation (CV), genetic features (frequency components) selection, EL, DL, layered learning, genetic optimization of classifiers parameters, and new genetic layered training (expert votes selection) to connect classifiers.

Novel contributions of this work are based on works [12, 13, 22, 23], focused on:

- N1 New deep multilayered structure of the system (ensemble of classifiers) provides appropriate information flow and fusion.
- N2 New method of combining the system nodes (classifiers) based on genetic layered training (selection of classifiers/experts answers/votes).

### 1.4 Previous research

The work described in the article includes stage III of conducted research, and the remaining stages Nos. I and II are described in earlier articles:

- Stage I —the focus was on designing and testing methods for signal preprocessing, feature extraction, selection, and CV. In this type of work, only single classical classifiers were tested, optimized by genetic algorithm (GA). A description of this type of work is presented in the article [52].
- Stage II —the focus was on developing ML methods by designing, optimizing and testing a genetic (two layers, 18 or 11 classifiers) ensemble of classifiers, combining the advantages of EL and EC. In this research, only one type of classifier and one path of signal preprocessing

and feature extraction were used. A description of this research is presented in the article [51].

Stage III —the focus was on further developing ML methods by designing, optimizing and testing a more complex deep genetic (three layers, 53 classifiers) ensemble of classifiers combining the advantages of EL [21, 37, 38, 47, 62, 72], EC [14, 28] and DL [11, 16, 17, 27, 32, 39, 63]. In this research, four types of classifiers and 12 paths of signal preprocessing and feature extraction were used. This increase in diversity has increased the efficiency of the system. A description of this research is presented in this article.

The concept of ECG signal analysis presented in this article is based on previous research, but the solution proposed, in a decisive way, differs from previous works. The proper direction of development of the proposed idea resulted in obtaining definitely better results.

## 2 Materials and methods

### 2.1 Assumptions

The described study is based on the new methodology presented in articles [51, 52]. The main assumptions of the new methodology are as follows:

- A1 Analysis 10-s segments of ECG signal (longer than single QRS complexes).
- A2 No signal filtering
- A3 No detection and segmentation of QRS complexes.
- A4 Use of feature extraction comprising the estimation of the power spectral density.
- A5 Use of feature (frequency components) selection based on GA.
- A6 Analysis of ECG signal segments contains one type of class (with the exception of normal sinus rhythm) abnormality.
- A7 Use of stratified tenfold CV method
- A8 Use of the Winner-Takes-All (WTA) rule to classification of the ECG signal samples.

The use of the new approach has the following benefits: (1) reduced number of classifications (average 13 times, for a heart rate of 80 beats per minute) and (2) eliminating the detection and segmentation of QRS complexes. These advantages reduce the computational complexity, which enabled the use of the proposed solution in cloud computing or mobile devices (real-time processing). Also analyzing longer segments of ECG signal gives better

outcomes for the classification of few diseases, for example, atrial-sinus and atrioventricular conduction blocks, Wolff–Parkinson–White syndrome, and elongates PQ intervals [52].

### 2.2 Materials

#### 2.2.1 ECG dataset

The ECG signals were obtained from the MIT-BIH Arrhythmia [45] database from the PhysioNet [31] service. The details of the data used are given below.

- The ECG signals were from 29 persons: 14 male (age: 32–89) and 15 female (age: 23–89).
- The ECG signals contained 17 classes: normal sinus rhythm, 15 types of cardiac arrhythmias and pacemaker rhythm.
- The ECG signals characteristics: (a) sampling frequency equal to 360 (HZ) and (b) gain equal to 200 (adu/mV).
- 744 ECG signal segments (10 s long, 3600 samples, without any overlapping) were randomly selected.
- The ECG signals were derived from one lead (MLII).
- The ECG signals contained at least ten segments for each recognized class.

Table 1 describes the details of the dataset used. It presents the analyzed ECG signal segments of cardiac dysfunctions: (a) the number of obtained for all dysfunction ECG segments, (b) the number of persons from whom the ECG segments were obtained, and (c) the division of ECG signal segments into training and testing sets for stratified tenfold CV.

The appropriate balance of data is an important aspect. In the research, a number of analyzed segments of ECG signal for all classes are in the range from 1.34% to 25.94%, imbalance ratio (IR) = 19, (see Table 1). More information about the dataset used can be found in the article [51].

### 2.3 Methods

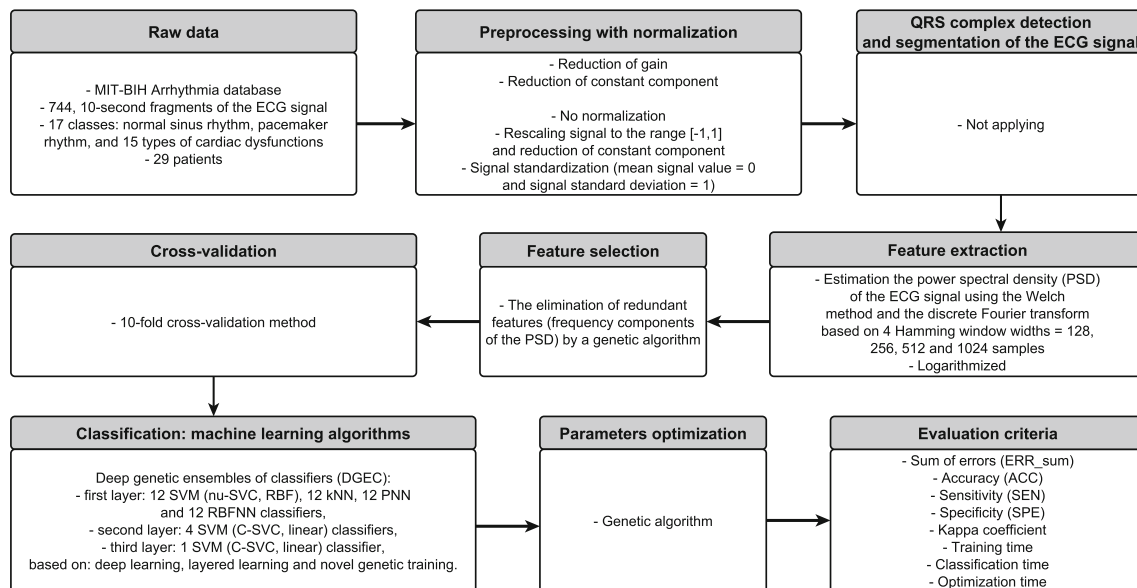
In Fig. 1, subsequent phases of processing and analysis of the ECG signals are presented.

#### 2.3.1 Phase I: preprocessing with normalization

Gain reduction and constant component reduction were used. Three types of normalization were tested: (a) **standardization** of signal (signal standard deviation = 1 and mean signal value = 0), (b) **rescaling** of signal to the range of  $[-1, 1]$  + reduction of constant component, and (c) **lack**

**Table 1** Dataset description with randomly selected segments of ECG signals and segments division by stratified tenfold CV into testing and training sets [51]

No.	Class	Stratified tenfold CV				Segments number	Patients number
		Groups 1–9		Group 10			
		Training set	Testing set	Training set	Testing set		
1	Normal sinus rhythm (NSR)	174	19	171	22	193	14
2	Atrial premature beat (APB)	53	5	45	13	58	8
3	Atrial flutter (AFL)	16	1	9	8	17	2
4	Atrial fibrillation (AFIB)	84	9	81	12	93	3
5	Supraventricular tachyarrhythmia (SVTA)	10	1	9	2	11	3
6	Pre-excitation (WPW)	19	2	18	3	21	1
7	Premature ventricular contraction (PVC)	71	7	63	15	78	9
8	Ventricular bigeminy (BIG)	40	4	36	8	44	4
9	Ventricular trigeminy (TRI)	12	1	9	4	13	4
10	Ventricular tachycardia (VT)	9	1	9	1	10	3
11	Idioventricular rhythm (IVR)	9	1	9	1	10	1
12	Ventricular flutter (VFL)	9	1	9	1	10	1
13	Fusion of ventricular and normal beat (FUS)	10	1	9	2	11	3
14	Left bundle branch block beat (LBBBB)	80	8	72	16	88	2
15	Right bundle branch block beat (RBBBB)	43	4	36	11	47	2
16	Second-degree heart block (SDHB)	9	1	9	1	10	1
17	Pacemaker rhythm (PR)	27	3	27	3	30	1
	Sum	675	69	621	123	744	29

**Fig. 1** Best path (methods combination) describing subsequent phases of processing and analysis of ECG signal segments

**of normalization.** More information about signal preprocessing can be found in article [52].

### 2.3.2 Phase II: feature extraction

First, power spectral density (PSD) [64] of ECG signal was estimated based on Welch method [70] and discrete Fourier transform (DFT) [64]. Subsequently, the transformed signal was logarithmized to normalize the frequency components of the PSD. **Four Hamming window widths: (a) 128, (b) 256, (c) 512, and (d) 1024 samples,** were used to calculate the PSD. More information about feature extraction can be found in articles [51, 52].

### 2.3.3 Phase III: feature selection

Three methods have been tested: (a) no selection, (b) selection based on GA [14, 59], and (c) selection based on particle swarm optimization (PSO [36]). The **selection based on GA** has obtained the best result and GA was applied for feature (frequency components) selection. Successive single ECG signal features (given as the inputs data of the classifiers) are represented as genes in the population of individuals. The following values can take genes: 0—rejected feature or 1—accepted feature. GA parameters are described in Tables 2 and 3.

### 2.3.4 Phase IV: cross-validation

Two methods have been tested: (a) stratified fourfold CV and (b) stratified tenfold CV [38]. **Stratified tenfold CV method** has obtained the best results. The testing and training sets were created by randomly selecting ECG signal segments separately for each class, maintaining the proportions between classes. Table 1 presents the selection of signal segments into training and testing sets. Stratified CV means that each set has proportional number of instances from all the classes. More information about the CV can be found in the article [51].

### 2.3.5 Phase V: machine learning algorithms

Nine methods have been tested: (a) support vector machine (SVM [19, 20], types: C-SVC, nu-SVC, nu-SVR, and epsilon-SVR), (b) probabilistic neural network (PNN, [67]), (c) k-nearest neighbor (kNN, [10]), (d) radial basis function neural network (RBFNN, [18]), (e) Takagi–Sugeno fuzzy system [69], (f) decision tree [56], (g) multilayer perceptron, (h) recurrent neural networks [55], and (i) discriminant analysis [44]. The results obtained due to the best performing **classifiers, namely kNN, RBFNN, PNN, and SVM (nu-SVC and C-SVC)** (Table 4), were

presented. Parameters of the mentioned classifiers are presented in Tables 2 and 5.

### 2.3.6 Phase VI: parameter optimization

Three methods have been tested: (a) particle swarm optimization, (b) GA, and (c) grid search. Among them, **GA** has achieved the best results. Tables 2 and 3 describe the GA parameters used.

### 2.3.7 Evolutionary neural system

For single classifiers, the evolutionary neural systems comprising the SVM, kNN, PNN, and RBFNN classifiers have obtained the best results. The core of the evolutionary neural system is the classifier optimized using the GA. The selection of features and the optimization of the classifier parameters were carried out using a GA coupled with a stratified tenfold CV method.

### 2.3.8 Classical ensembles of classifiers (CEC)

A classic, two-layer *bagging*-type ensemble of classifiers were used. The first layer consisted of ten SVM classifiers (nu-SVC). SVMs are trained on the basis of the subsequent ten combinations of testing and training sets from stratified tenfold CV. In the second layer, the answers of classifiers from the first layer were combined using the majority voting method. The GA was used to optimize the CEC system.

## 2.4 Deep genetic ensemble of classifiers (DGEC)

DGEC is three-layer ( $48 + 4 + 1$ ) system. In the DGEC system, each classifier of the first layer is optimized in order to maximize the accuracy of arrhythmia classification. In the second layer and third layer, based on the classifier answers from the first layer and based on **DL and genetic selection of features**, knowledge extraction process occurs leading to the final decision by the system.

In the previous work, we designed and tested: (1) genetic ensemble of classifiers optimized by classes (GECC system) and (2) genetic ensemble of classifiers optimized by sets (GECS system), described in [51].

### 2.4.1 Philosophy

The inspiration for the DGEC system was approach based on DL mimic nature on mechanisms occurring in the neocortex of the brain.

Characteristic features of system are as follows:

- **Classifiers as neurons**, connected in network.

**Table 2** Information about the **first layer** of DGEC system

1st layer of DGEC system	
Optimization of classifier parameters and selection of features	
Optimization of classifier parameters and selection of features were performed by GA coupled with the stratified tenfold CV	
Genetic algorithm	<p>Number of individuals: 50;</p> <p>Gene representation type: vectors of floating point;</p> <p>Chromosome structure of individual: vector of floating point of the construction <math>[g_1, g_2, f_1, \dots, f_{4001}]</math> for <i>SVM</i>, where <math>g_1</math>—the first gene, specifying the value of the first parameter <math>-g, (\gamma)</math>, <math>g_2</math>—the second gene, specifying the value of the second parameter <math>-n (v)</math>, and <math>f_1, \dots, f_{4001}</math>—4001 genes (values in the range of <math>[0, 1]</math>, specifying the selection of features, rounded to the values: (a) 1—accepted feature, or (b) 0—rejected feature). Chromosome contained one gene, <math>g</math> (specifying the value of one optimizing parameter) for other classifiers (<i>RBFFNN</i>, <i>PNN</i>, <i>kNN</i>);</p> <p>Initial population: uniform and random;</p> <p>Genes value range in initial population: for selection of features = <math>[0, 1]</math>; for optimization of classifier parameters, local ranges for respective classifiers are presented in <i>Optimizing parameters</i> section (experimentally chosen based on global (broader) ranges)</p> <p>Fitness function target value: 0;</p> <p>Maximum number of generations: <math>20 \vee 30</math>;</p> <p>Crossover type: intermediate; Crossover probability: 0.7;</p> <p>Mutation type: uniform; mutation probability: 0.3;</p> <p>Number of best individuals who survived with no change: 3;</p> <p>Method of scaling the fitness function value: ranking;</p> <p>Parent selection method: tournament;</p> <p>Formula for calculating the fitness function:</p> $ERR = w_l \cdot err_{Lsum} + w_t \cdot err_{Tsum} + w_f \cdot \frac{F_{\theta}}{F} \quad (1)$ <p>where:</p> <p><math>w_l</math> = 1—weight for training sets errors;</p> <p><math>w_t</math> = 1—weight for testing sets errors;</p> <p><math>w_f</math> = 1—weight for <math>C_F</math>;</p> <p><math>err_{Lsum}</math>—sum of errors in all ten training sets;</p> <p><math>err_{Tsum}</math>—sum of errors in all ten testing sets;</p> <p><math>\frac{F_{\theta}}{F} = C_F</math> (formula 8 in Sect. 2.5);</p> <p>Number of features has been reduced about two times (from 4001 to 2000 frequency components) as a result of used selection of features—Table 5;</p>
<b>Classifiers</b>	
48 trained, tested, and optimized classifiers— <i>experts</i> :	
Four classifier types · four Hamming window widths · three signal preprocessing types · one CV type	
<b>Basic parameters</b>	
SVM	<p>Type: nu-SVC (support vector classification);</p> <p>Type of kernel function: RBF (radial basis function, Gaussian type);</p> <p>Number of outputs = 17, from the set: <math>\{0, 1\}</math>;</p>
kNN	<p>Number of nearest neighbors = 1;</p> <p>Distance calculation metric: <i>Minkowski</i>;</p> <p>Number of outputs = 17, from the set: <math>\{0, 1\}</math>;</p>
PNN	<p>Activation (transfer) function: RBF (radial basis function, Gaussian type) in first layer and competition in second layer;</p> <p>Training algorithm: training set mapping based on distance;</p> <p>Objective function calculating type: Sum of Square Errors (SSE);</p> <p>Topology (neurons): inputs (feature vector length)—<math>675 \vee 621-17</math>; Biases: 1–0;</p> <p>Number of outputs = 17, from the set: <math>\{0, 1\}</math>;</p>
RBFFNN	<p>Activation (transfer) function: RBF (radial basis function, Gaussian type) in first layer and linear in second layer;</p> <p>Training algorithm: mapping the training set based on a distance;</p> <p>Objective function calculating type: Sum of Square Errors (SSE);</p>



**Table 2** continued**1st layer of DGEC system****Optimization of classifier parameters and selection of features**

Optimization of classifier parameters and selection of features were performed by GA coupled with the stratified tenfold CV

Topology (neurons): inputs (feature vector length)—675  $\vee$  621–17; Biases: 1–1;  
 Number of outputs = 17, from the set: {0, 1}. Value “1” assigned to the highest stimulus output (class);

**Optimizing parameters**

Based on a broader range were chosen experimentally final parameter ranges.

SVM	$-g$ ( $\gamma$ ) parameter specifying spread of RBF kernel function from the range: $[2 \times 10^{-6}; 2 \times 10^{-4}]$ (1500 values = 30 (generations number) $\cdot$ 50 (individuals number) and resolution equal to $10^{-14}$ ); $-n$ ( $\nu$ ) parameter specifying margins width from range: [0.001; 0.05] (1500 values = 30 (generations number) $\cdot$ 50 (individuals number) and resolution equal to $10^{-14}$ );
kNN	<i>Exponent</i> parameter specifying Minkowski distance from the range: [0.01; 100] (1000 values = 20 (generations number) $\cdot$ 50 (individuals number) and resolution equal to $10^{-14}$ );
PNN	<i>Spread</i> parameter specifying spread of RBF kernel function from the range: [1; 100] (1000 values = 20 (generations number) $\cdot$ 50 (individuals number) and resolution equal to $10^{-14}$ );
RBFNN	<i>Spread</i> parameter specifying spread of RBF kernel function from the range: [1; 300] (1000 values = 20 (generations number) $\cdot$ 50 (individuals number) and resolution equal to $10^{-14}$ );

**Table 3** Information about second and third layer of DGEC system**Second and third layer of DGEC system****Selection of features**

Selection of features was performed by GA coupled with the stratified tenfold CV

Genetic algorithm	<p>Number of individuals: 200 in second layer and 100 in third layer;</p> <p>Gene representation type: string of bits in second and third layer;</p> <p>Chromosome structure of individual: in second layer: vector of bits of the construction: <math>[f_1, \dots, f_{204}]</math>, consisting of 204 genes (values from the set: {0, 1}, where: 1—accepted feature, or 0—rejected feature); in third layer: vector of bits of the construction: <math>[f_1, \dots, f_{68}]</math>, consisting of 68 genes (values from the set: {0, 1}, where: 1—accepted feature, or 0—rejected feature)</p> <p>Initial population: uniform and random in second and third layer;</p> <p>Gene value range in the initial population: in second and third layer from the set: {0, 1};</p> <p>Fitness function target value: 0 for second and third layer;</p> <p>Maximum number of generations: 100 in second and third layer;</p> <p>Crossover type: scattered in second and third layer; crossover probability: 0.9 in second and third layer;</p> <p>Mutation type: uniform in second and third layer; mutation probability: 0.1 in second and third layer;</p> <p>Number of best individuals who survived with no change: 10 in second and third layer;</p> <p>Method of scaling the fitness function value: ranking in second and third layer;</p> <p>Parent selection method: tournament in second and third layer;</p> <p>Formula for calculating the fitness function is given in Table 2, equation 1</p> <p>The number of features has been reduced about two times in second layer (from 204 to 100 classifier answers/votes), and about three times in third layer (from 68 to 25 classifier answers/votes) as a result of used selection of features—Table 6;</p>
-------------------	---

**Classifiers**

In second layer: four optimized, trained and tested classifiers—*judges* (one classifier type  $\cdot$  one CV type)

In third layer: one optimized, trained and tested classifier—*judge* (one classifier type  $\cdot$  1 CV type)

**Basic parameters**

SVM	<p>Type: C-SVC in second and third layer;</p> <p>Type of kernel function: linear in second and third layer;</p> <p>Number of outputs: 17, from the set: {0, 1} in second layer, and 1, from the set: {1, <math>\dots</math>, 17} in third layer;</p> <p><math>-c</math> (<i>cost</i>) parameter specifying the margins equal to the default value = 1;</p>
-----	--

**Optimizing parameters**

Lack

**Table 4** A comparison of achieved outcomes

Coefficients	Methods					
	Single classifiers				Ensembles of classifiers	
	kNN	RBFNN	PNN	SVM	CEC	DGEC
Classifier	<i>kNN</i>	<i>RBFNN</i>	<i>PNN</i>	<i>SVM</i>	<i>SVM</i>	<i>SVM</i>
$ERR_{sum}$	<b>79</b>	79	77	73	75	<b>40</b>
$ACC$	98.75%	98.75%	98.78%	98.85%	98.81%	99.37%
$SEN$	<b>89.38%</b>	89.38%	89.65%	90.19%	89.92%	<b>94.62%</b>
$SPE$	99.34%	99.34%	99.35%	99.39%	99.37%	99.66%
$\kappa$	87.84%	87.84%	88.14%	88.70%	88.38%	93.84%
$C_F$	78.26%	47.86%	49.51%	49.09%	48.84%	47.31%
$T_t$ (s)	0.1432	54.0503	0.3316	11.3537	115.8115	821.5928
$T_c$ (s)	0.0853	0.0077	0.0055	0.0018	0.0186	0.8736

Sum of errors is zero for all training sets. The worst results are in bold italic, and the best in bold

- **Layered learning**—as in DL, the learning is progressing in stages.
- **Genetic layered training:**
  - **Optimization of connections** between classifiers from adjacent layers (feature selection) realized by a GA is analogous to the elimination of connections in the brain between neurons.
  - **Feedback** occurring during training in the form of a GA (genetic optimization) and in the form of CV (training) is similar to back-connections in brain.
- **Diversity** is present in classifiers, data preprocessing, and connections and is analogous to the different types of neurons, signal processing and irregular connections between neurons belonging to the neo-cortex of brain. The diversity of **classifiers** (four types) is included in the first layer. The diversity of **data preprocessing** is present in the first layer (three types of normalization and four types of Hamming window widths). The diversity of **connections** is between first and second layer and between second and third layer because do not occur all possible connections between the classifiers.
- **Bipolarity** is noticeable by the value of transmitted signals from the set:  $\{0; 1\}$  similar to the value of the action potential of nerve cells (neurons).
- **Multilayered (depth)**—according to the definition of DL, networks that have in their structure above two layers are considered as deep, which is analogous to the neocortex of brain, and it consists of seven layers.
- **Abstract learning** is in the form of the internal extraction of features and transforming information

in subsequent layers of its structure which generates more complex features that are abstract concepts, like in the brain.

The deep structure of designed system (network) consists of three layers, and the term **genetic** implies that in this research, GA plays a key role and **ensemble of classifiers** is comprised of 53 classifiers (nodes).

Layered learning—the first supervised training was performed for 48 classifiers from the first layer. The second supervised training was performed for four classifiers from the second layer based on the answers received from 48 models of classifiers from the first layer. The third supervised training was performed for one classifier from the third layer based on the answers received from four models of classifiers from the second layer.

Cross-validation—the stratified tenfold CV was coupled with GA (in first, second, and third layer of DGEC system), and all individuals (feature vectors) in the population were tested on all ten testing sets and ten training sets. This solution minimizes over-training.

First layer

- **Genetic feature selection** was used to feature (frequency components) **selection** and parameter **optimization** for 48 classifiers in the first layer.
- **Optimization** was done by GA (Table 2), and its purpose is parallel: (a) selection of ECG signal features and (b) optimization of classifier parameters (system nodes).
- **Votes (answers)**—all classifiers (*experts*) have 17 outputs each with value of “0” or “1”. Value “1” occurs only in one output (indicated recognized, by



**Table 5** Results for 48 classifiers from the first layer of DGEC system, for stratified tenfold CV

Normalization:	Window width:	Classifiers			
		SVM	kNN	PNN	RBFNN
No normalization	128 samples	$-g = 9.89\text{e-}5$			
		$-n = 0.0087$	$exponent = 2.38$	$spread = 13.94$	$spread = 70.28$
		$ERR_{sum} = 99$	$ERR_{sum} = \mathbf{125}$	$ERR_{sum} = 116$	$ERR_{sum} = 101$
		$ACC = 98.44\%$	$ACC = 98.02\%$	$ACC = 98.17\%$	$ACC = 98.40\%$
		$SEN = 86.69\%$	$SEN = 83.20\%$	$SEN = 84.41\%$	$SEN = 86.43\%$
		$SPE = 99.17\%$	$SPE = 98.95\%$	$SPE = 99.03\%$	$SPE = 99.15\%$
		$\kappa = 84.67\%$	$\kappa = 80.71\%$	$\kappa = 82.11\%$	$\kappa = 84.40\%$
		$C_F = 49.29\%$	$C_F = 49.16\%$	$C_F = 47.99\%$	$C_F = 48.76\%$
		$T_t = 12.5594$ (s)	$T_t = 0.1074$ (s)	$T_t = 0.4257$ (s)	$T_t = 57.4693$ (s)
		$T_c = 0.0018$ (s)	$T_c = 0.0511$ (s)	$T_c = 0.0060$ (s)	$T_c = 0.0080$ (s)
	256 samples	$-g = 4.24\text{e-}5$			
		$-n = 0.0167$	$exponent = 2.00$	$spread = 13.22$	$spread = 115.96$
		$ERR_{sum} = 98$	$ERR_{sum} = 109$	$ERR_{sum} = 104$	$ERR_{sum} = 109$
		$ACC = 98.45\%$	$ACC = 98.28\%$	$ACC = 98.36\%$	$ACC = 98.28\%$
		$SEN = 86.83\%$	$SEN = 85.35\%$	$SEN = 86.02\%$	$SEN = 85.35\%$
		$SPE = 99.18\%$	$SPE = 99.08\%$	$SPE = 99.13\%$	$SPE = 99.08\%$
		$\kappa = 84.84\%$	$\kappa = 83.20\%$	$\kappa = 83.96\%$	$\kappa = 83.16\%$
		$C_F = 50.61\%$	$C_F = 72.31\%$	$C_F = 50.94\%$	$C_F = 50.94\%$
		$T_t = 11.9220$ (s)	$T_t = 0.1163$ (s)	$T_t = 0.4521$ (s)	$T_t = 56.6089$ (s)
		$T_c = 0.0020$ (s)	$T_c = 0.0747$ (s)	$T_c = 0.0065$ (s)	$T_c = 0.0076$ (s)
	512 samples	$-g = 3.74\text{e-}5$			
		$-n = 0.0051$	$exponent = 3.70$	$spread = 20.56$	$spread = 79.55$
		$ERR_{sum} = 83$	$ERR_{sum} = 103$	$ERR_{sum} = 97$	$ERR_{sum} = 97$
		$ACC = 98.69\%$	$ACC = 98.37\%$	$ACC = 98.47\%$	$ACC = 98.47\%$
		$SEN = 88.84\%$	$SEN = 86.16\%$	$SEN = 86.96\%$	$SEN = 86.96\%$
		$SPE = 99.30\%$	$SPE = 99.14\%$	$SPE = 99.19\%$	$SPE = 99.19\%$
		$\kappa = 87.14\%$	$\kappa = 84.14\%$	$\kappa = 85.03\%$	$\kappa = 84.99\%$
		$C_F = 49.24\%$	$C_F = 50.04\%$	$C_F = 49.09\%$	$C_F = 49.11\%$
		$T_t = 12.4013$ (s)	$T_t = 0.1074$ (s)	$T_t = 0.5083$ (s)	$T_t = 46.8782$ (s)
		$T_c = 0.0020$ (s)	$T_c = 0.0518$ (s)	$T_c = 0.0061$ (s)	$T_c = 0.0061$ (s)
1024 samples	$-g = 2.08\text{e-}5$				
	$-n = 0.0122$	$exponent = 2.95$	$spread = 26.88$	$spread = 140.02$	
	$ERR_{sum} = 85$	$ERR_{sum} = 92$	$ERR_{sum} = 83$	$ERR_{sum} = 94$	
	$ACC = 98.66\%$	$ACC = 98.55\%$	$ACC = 98.69\%$	$ACC = 98.51\%$	
	$SEN = 88.58\%$	$SEN = 87.63\%$	$SEN = 88.84\%$	$SEN = 87.37\%$	
	$SPE = 99.29\%$	$SPE = 99.23\%$	$SPE = 99.30\%$	$SPE = 99.21\%$	
	$\kappa = 86.84\%$	$\kappa = 85.84\%$	$\kappa = 87.19\%$	$\kappa = 85.40\%$	
	$C_F = 48.34\%$	$C_F = 49.39\%$	$C_F = 49.49\%$	$C_F = 50.24\%$	
	$T_t = 14.7607$ (s)	$T_t = 0.1130$ (s)	$T_t = 0.4349$ (s)	$T_t = 41.1444$ (s)	
	$T_c = 0.0021$ (s)	$T_c = 0.0503$ (s)	$T_c = 0.0061$ (s)	$T_c = 0.0057$ (s)	
Rescaling + reduction of constant component	128 samples	$-g = 8.04\text{e-}5$			
		$-n = 0.0114$	$exponent = 3.35$	$spread = 15.78$	$spread = 71.94$
		$ERR_{sum} = 91$	$ERR_{sum} = 93$	$ERR_{sum} = 98$	$ERR_{sum} = 93$
		$ACC = 98.56\%$	$ACC = 98.53\%$	$ACC = 98.45\%$	$ACC = 98.53\%$
		$SEN = 87.77\%$	$SEN = 87.50\%$	$SEN = 86.83\%$	$SEN = 87.50\%$
		$SPE = 99.24\%$	$SPE = 99.22\%$	$SPE = 99.18\%$	$SPE = 99.22\%$
		$\kappa = 85.94\%$	$\kappa = 85.68\%$	$\kappa = 84.89\%$	$\kappa = 85.57\%$

Table 5 continued

Normalization:	Window width:	Classifiers			
		SVM	kNN	PNN	RBFNN
	256 samples	$C_F = 46.74\%$	$C_F = 48.21\%$	$C_F = 48.46\%$	$C_F = 49.89\%$
		$T_t = 9.7303$ (s)	$T_t = 0.1142$ (s)	$T_t = 0.4301$ (s)	$T_t = 60.9248$ (s)
		$T_c = 0.0016$ (s)	$T_c = 0.0492$ (s)	$T_c = 0.0060$ (s)	$T_c = 0.0084$ (s)
		$-g = 4.81\text{e}-5$			
		$-n = 0.0125$	$exponent = 3.47$	$spread = 11.19$	$spread = 136.77$
		$ERR_{sum} = 87$	$ERR_{sum} = 90$	$ERR_{sum} = 92$	$ERR_{sum} = 86$
		$ACC = 98.62\%$	$ACC = 98.58\%$	$ACC = 98.55\%$	$ACC = 98.64\%$
		$SEN = 88.31\%$	$SEN = 87.90\%$	$SEN = 87.63\%$	$SEN = 88.44\%$
		$SPE = 99.27\%$	$SPE = 99.24\%$	$SPE = 99.23\%$	$SPE = 99.28\%$
		$\kappa = 86.53\%$	$\kappa = 86.13\%$	$\kappa = 85.83\%$	$\kappa = 86.70\%$
		$C_F = 49.39\%$	$C_F = 49.99\%$	$C_F = 50.21\%$	$C_F = 49.59\%$
		$T_t = 10.6013$ (s)	$T_t = 0.1356$ (s)	$T_t = 0.3270$ (s)	$T_t = 59.0492$ (s)
		$T_c = 0.0018$ (s)	$T_c = 0.0541$ (s)	$T_c = 0.0055$ (s)	$T_c = 0.0076$ (s)
	512 samples	$-g = 2.64\text{e}-5$			
		$-n = 0.0183$	$exponent = 3.61$	$spread = 18.85$	$spread = 117.89$
		$ERR_{sum} = 73$	$ERR_{sum} = 87$	$ERR_{sum} = 80$	$ERR_{sum} = 80$
		$ACC = 98.85\%$	$ACC = 98.62\%$	$ACC = 98.74\%$	$ACC = 98.74\%$
		$SEN = 90.19\%$	$SEN = 88.31\%$	$SEN = 89.25\%$	$SEN = 89.25\%$
		$SPE = 99.39\%$	$SPE = 99.27\%$	$SPE = 99.33\%$	$SPE = 99.33\%$
		$\kappa = 88.70\%$	$\kappa = 86.60\%$	$\kappa = 87.65\%$	$\kappa = 87.63\%$
		$C_F = 49.09\%$	$C_F = 49.59\%$	$C_F = 49.76\%$	$C_F = 50.81\%$
		$T_t = 11.3537$ (s)	$T_t = 0.1192$ (s)	$T_t = 0.3194$ (s)	$T_t = 56.8192$ (s)
		$T_c = 0.0018$ (s)	$T_c = 0.0597$ (s)	$T_c = 0.0055$ (s)	$T_c = 0.0076$ (s)
	1024 samples	$-g = 7.69\text{e}-6$			
		$-n = 0.0105$	$exponent = 2.34$	$spread = 20.11$	$spread = 148.12$
		$ERR_{sum} = 74$	$ERR_{sum} = 79$	$ERR_{sum} = 77$	$ERR_{sum} = 79$
		$ACC = 98.83\%$	$ACC = 98.75\%$	$ACC = 98.78\%$	$ACC = 98.75\%$
		$SEN = 90.05\%$	$SEN = 89.38\%$	$SEN = 89.65\%$	$SEN = 89.38\%$
		$SPE = 99.38\%$	$SPE = 99.34\%$	$SPE = 99.35\%$	$SPE = 99.34\%$
		$\kappa = 88.53\%$	$\kappa = 87.84\%$	$\kappa = 88.14\%$	$\kappa = 87.73\%$
		$C_F = 47.91\%$	$C_F = 78.26\%$	$C_F = 49.51\%$	$C_F = 47.86\%$
		$T_t = 10.4768$ (s)	$T_t = 0.1432$ (s)	$T_t = 0.3316$ (s)	$T_t = 54.0503$ (s)
		$T_c = 0.0019$ (s)	$T_c = 0.0853$ (s)	$T_c = 0.0055$ (s)	$T_c = 0.0077$ (s)
Standardization	128 samples	$-g = 1.59\text{e}-4$			
		$-n = 0.0290$	$exponent = 5.55$	$spread = 17.95$	$spread = 88.52$
		$ERR_{sum} = 103$	$ERR_{sum} = 123$	$ERR_{sum} = 120$	$ERR_{sum} = 107$
		$ACC = 98.37\%$	$ACC = 98.06\%$	$ACC = 98.10\%$	$ACC = 98.31\%$
		$SEN = 86.16\%$	$SEN = 83.47\%$	$SEN = 83.87\%$	$SEN = 85.62\%$
		$SPE = 99.14\%$	$SPE = 98.97\%$	$SPE = 98.99\%$	$SPE = 99.10\%$
		$\kappa = 84.04\%$	$\kappa = 81.03\%$	$\kappa = 81.47\%$	$\kappa = 83.44\%$
		$C_F = 48.84\%$	$C_F = 47.69\%$	$C_F = 48.59\%$	$C_F = 49.34\%$
		$T_t = 16.9512$ (s)	$T_t = 0.1331$ (s)	$T_t = 0.3458$ (s)	$T_t = 64.2180$ (s)
		$T_c = 0.0018$ (s)	$T_c = 0.0525$ (s)	$T_c = 0.0054$ (s)	$T_c = 0.0089$ (s)

**Table 5** continued

Normalization:	Window width:	Classifiers			
		SVM	kNN	PNN	RBFNN
	256 samples	$-g = 4.80e-5$			
		$-n = 0.0126$	$exponent = 2.64$	$spread = 14.98$	$spread = 77.97$
		$ERR_{sum} = 97$	$ERR_{sum} = 122$	$ERR_{sum} = \mathbf{121}$	$ERR_{sum} = 110$
		$ACC = 98.47\%$	$ACC = 98.07\%$	$ACC = 98.09\%$	$ACC = 98.26\%$
		$SEN = 86.96\%$	$SEN = 83.60\%$	$SEN = 83.74\%$	$SEN = 85.22\%$
		$SPE = 99.19\%$	$SPE = 98.98\%$	$SPE = 98.98\%$	$SPE = 99.08\%$
		$\kappa = 85.02\%$	$\kappa = 81.22\%$	$\kappa = 81.33\%$	$\kappa = 83.00\%$
		$C_F = 50.56\%$	$C_F = 49.01\%$	$C_F = 49.16\%$	$C_F = 49.11\%$
		$T_t = 9.8686$ (s)	$T_t = 0.1586$ (s)	$T_t = 0.3504$ (s)	$T_t = 58.4766$ (s)
		$T_c = 0.0016$ (s)	$T_c = 0.0590$ (s)	$T_c = 0.0054$ (s)	$T_c = 0.0077$ (s)
	512 samples	$-g = 1.46e-5$			
		$-n = 0.0129$	$exponent = 3.61$	$spread = 24.35$	$spread = 193.28$
		$ERR_{sum} = 83$	$ERR_{sum} = 115$	$ERR_{sum} = 101$	$ERR_{sum} = \mathbf{112}$
		$ACC = 98.69\%$	$ACC = 98.18\%$	$ACC = 98.40\%$	$ACC = 98.23\%$
		$SEN = 88.84\%$	$SEN = 84.54\%$	$SEN = 86.43\%$	$SEN = 84.95\%$
		$SPE = 99.30\%$	$SPE = 99.03\%$	$SPE = 99.15\%$	$SPE = 99.06\%$
		$\kappa = 87.16\%$	$\kappa = 82.33\%$	$\kappa = 84.38\%$	$\kappa = 82.65\%$
		$C_F = 48.94\%$	$C_F = 48.61\%$	$C_F = 49.11\%$	$C_F = 50.14\%$
		$T_t = 9.2840$ (s)	$T_t = 0.1537$ (s)	$T_t = 0.3000$ (s)	$T_t = 58.8405$ (s)
		$T_c = 0.0017$ (s)	$T_c = 0.0583$ (s)	$T_c = 0.0052$ (s)	$T_c = 0.0077$ (s)
	1024 samples	$-g = 1.59e-5$			
		$-n = 0.0202$	$exponent = 14.08$	$spread = 25.90$	$spread = 171.45$
		$ERR_{sum} = 81$	$ERR_{sum} = 98$	$ERR_{sum} = 81$	$ERR_{sum} = 92$
		$ACC = 98.72\%$	$ACC = 98.45\%$	$ACC = 98.72\%$	$ACC = 98.55\%$
		$SEN = 89.11\%$	$SEN = 86.83\%$	$SEN = 89.11\%$	$SEN = 87.63\%$
		$SPE = 99.32\%$	$SPE = 99.18\%$	$SPE = 99.32\%$	$SPE = 99.23\%$
		$\kappa = 87.45\%$	$\kappa = 84.87\%$	$\kappa = 87.53\%$	$\kappa = 85.74\%$
		$C_F = 48.46\%$	$C_F = 51.26\%$	$C_F = 48.84\%$	$C_F = 48.64\%$
		$T_t = 12.9148$ (s)	$T_t = 0.1016$ (s)	$T_t = 0.2981$ (s)	$T_t = 58.0527$ (s)
		$T_c = 0.0020$ (s)	$T_c = 0.0469$ (s)	$T_c = 0.0052$ (s)	$T_c = 0.0079$ (s)

Sum of errors is zero for all training sets. The worst results are in bold italic, and the best in bold

the given classifier/*expert*, class, according to the WTA rule). Value “0” occurs on remaining 16 outputs (indicated not recognized classes).

#### Second and third layer

- **Genetic layered training** was used to tune the ensemble of classifiers structure in second and third layer, relying on feature selection (*experts or judges votes*) from the first or second layer, based on

reference answers. The aim of GA was to reject the incorrect answers (*votes*) of classifiers (nodes) from the first or second layer, based on the errors in all testing and training sets, and accept only correct answers (*votes*) as shown in Fig. 5. Genetic layered training is a novel approach of connecting classifiers (ensemble combination), and it is effective through transformation of one output into 17 outputs of classifiers.

**Table 6** Results for **second** and **third layer** of DGEC system. Sum of errors is zero for all training sets.  $ERR_L$  coefficient determines in all training sets sum of errors

Classifiers	Coefficients										
	$-c$	$ERR_L$	$ERR_{sum}$	$ACC$	$SEN$	$SPE$	$\kappa$	$C_F$	$T_t$	$T_c$	$T_o$
<b>The first layer of DGEC system—48 classifiers: SVM, kNN, PNN and RBFNN (3 normalization types and 4 Hamming window widths)—<i>experts</i></b>											
Detailed results of 48 classifiers from 1st layer were placed in Table 2											
<b>The second layer of DGEC system—4 SVM (C-SVC, linear) classifiers—<i>judges</i></b>											
$SVM_{49}(SVM)$	1	0	56	99.12%	92.47%	99.53%	91.35%	22.06%	0.0679 (s)	3.84e−6 (s)	about 1 (h)
$SVM_{50}(kNN)$	1	0	51	99.19%	93.15%	99.57%	92.14%	33.82%	0.0328 (s)	5.24e−6 (s)	about 1 (h)
$SVM_{51}(PNN)$	1	0	56	99.12%	92.47%	99.53%	91.37%	30.88%	0.0242 (s)	3.82e−6 (s)	about 1 (h)
$SVM_{52}(RBF)$	1	0	56	99.12%	92.47%	99.53%	91.34%	30.39%	0.0569 (s)	1.18e−5 (s)	about 1 (h)
<b>The third layer of DGEC system—1 SVM (C-SVC, linear) classifier—<i>judge</i></b>											
$SVM_{53}$	1	0	40	99.37%	94.62%	99.66%	93.84%	33.82%	0.0270 (s)	3.53e−6 (s)	about 0.5 (h)
<b>Summary</b>											
<b>DGEC system</b>	—	0	<b>40</b>	99.37%	<b>94.62%</b>	99.66%	<b>93.84%</b>	47.31%	821.5928 (s)	<b>0.8736</b> (s)	about 221 (h)

Bold values indicate the most important, final coefficients for the entire DGEC system

## 2.4.2 First layer

In the first layer of the system are 48 *experts* comprising of 12 SVM (nu-SVC, RBF), 12 kNN, 12 PNN, and 12 RBFNN classifiers (three types of normalization and four Hamming window widths) optimized to minimize errors in recognition of ECG signal classes. ECG signal segments comprising the most characteristic features (chosen using GA) are given to the inputs of each of the 48 classifiers. For each of the 48 classifiers, the different and optimal set of parameter values has been selected, for SVM:  $\gamma(-g)$ ,  $\nu(-n)$ , for kNN: *exponent*, for PNN: *spread*, and for RBFNN: *spread*.

## 2.4.3 Second layer

The second layer of the DGEC system has four *judges* with SVM classifiers (C-SVC, linear). These four meta-classifiers were developed in order to assess the *experts votes* from the first layer. Each of the *judges* was assigned to a group of 12 classifiers, which meant that the first *judge* evaluated the *votes* from 12 SVM classifiers, second from 12 kNN classifiers, third from 12 PNN classifiers, and fourth from 12 RBFNN classifiers. These 48 classifiers (from the first layer) have 17 outputs each, so the length of input features vector, to the second layer, is equal to 816 *votes*. Therefore, on the inputs of each of the four *judges* (classifiers from the second layer), 204 features are given.

## 2.4.4 Third layer

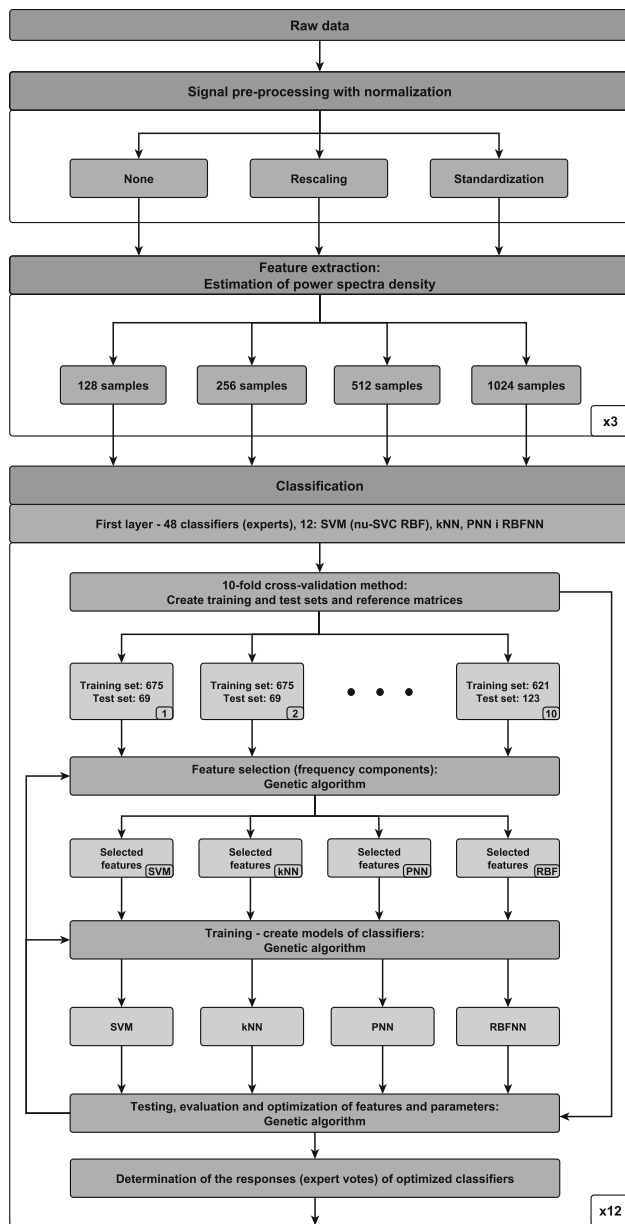
The third layer of the DGEC system has one *judge*, i.e., SVM classifier (C-SVC, linear). This one meta-classifier was designed to evaluate *judges votes* from the second layer. Four SVMs (from the second layer) have 17 outputs each, so the length of input features vector, to the third layer, is equal to 68 *votes*.

The analogous two-layer system (48 classifiers + 1 classifier) was also tested in the study. However, such a system was characterized by less effective training, which did not yield good ECG classification results. Therefore, this system is not widely discussed in the article. Hence, it can be concluded that another layer has contributed to boost the training efficiency of the system.

Many parameter configurations of GA and SVM, kNN, PNN, and RBFNN classifiers were tested as part of the study. The details of the optimization parameters are presented in Tables 2, 3, and 5.

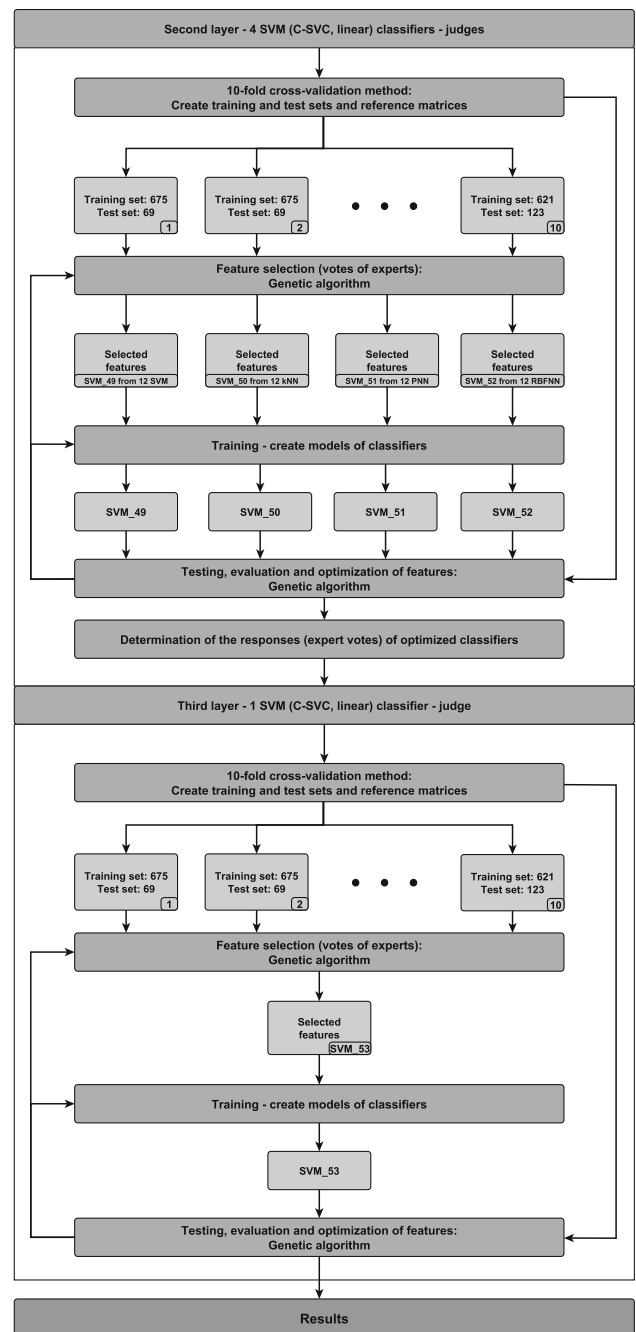
Basic and optimizing parameters of 48 classifiers from the **first layer** of DGEC system and GA parameters used for feature selection and optimization of classifier parameters are presented in Table 2.

Basic and optimizing parameters of (4 + 1) classifiers in **second** and **third layer** of DGEC system and GA parameters used for feature selection and optimization of classifier parameters are presented in Table 3.



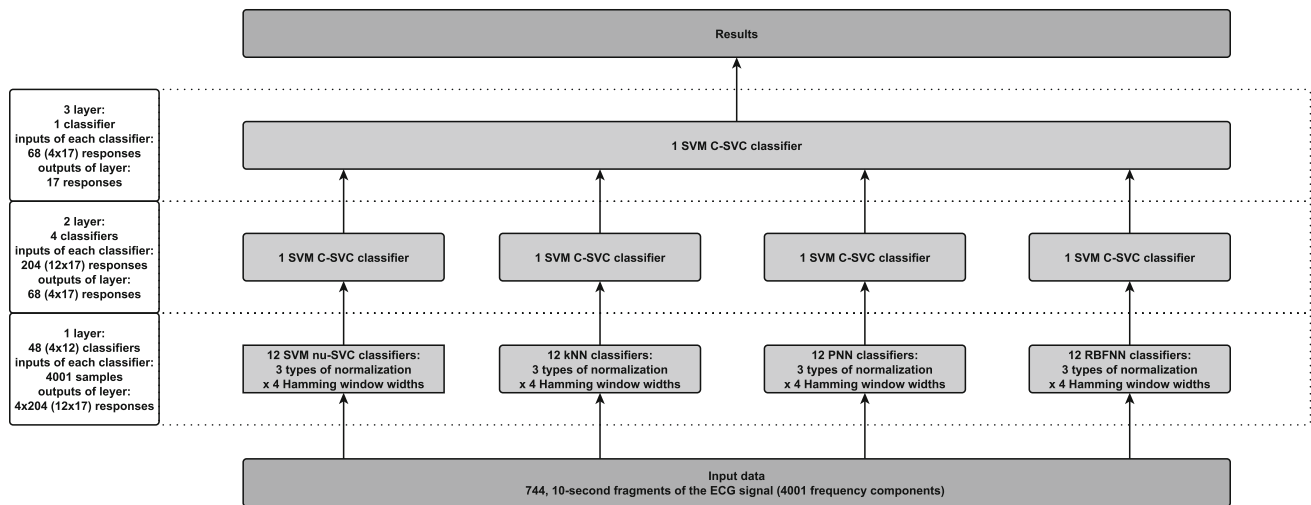
**Fig. 2** Part I of the scheme of subsequent phases of information processing (training and optimization of system) in *DGEC system*

Figures 2 and 3 show the scheme of subsequent phases of information processing in *DGEC system*. In Fig. 4, scheme of connections between layers, information flow and fusion in DGEC system is presented. Algorithm 1 and 2 present the DGEC system algorithm. Figure 5 presents

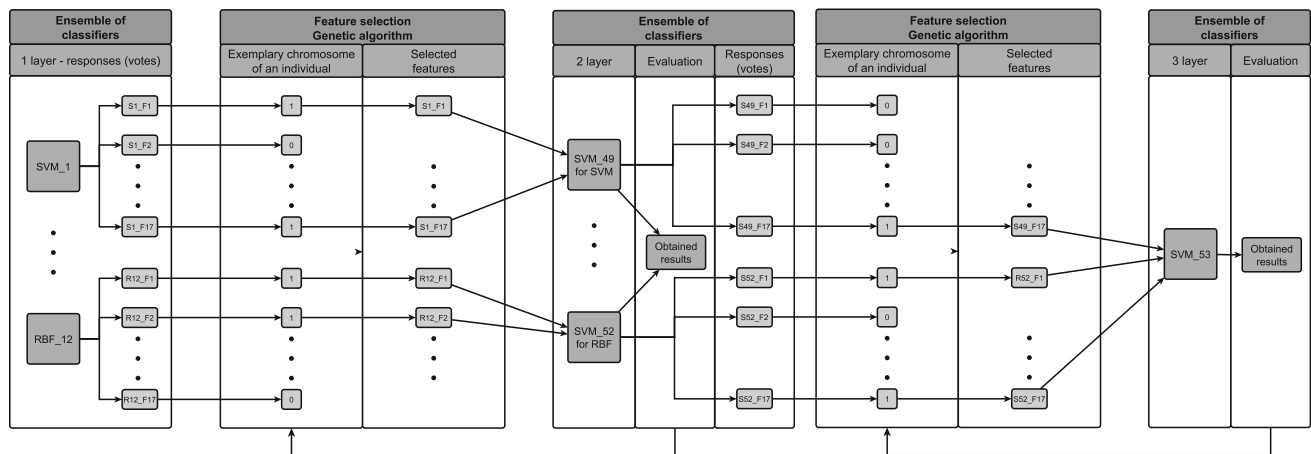


**Fig. 3** Part II of the scheme of subsequent phases of information processing (training and optimization of system) in *DGEC system*

the scheme of genetic layered training (for single segment of ECG signal and exemplary chromosomes of individuals).



**Fig. 4** Scheme of connections between layers, information flow and fusion to the *DGEC* system



**Fig. 5** Genetic layered training scheme, showing selection of features by GA, applied to combine classifiers, for exemplary chromosomes of individuals for one segment of ECG signal



**Algorithm 1: DGEC - Part I.**


---

**Data:**  
 $X$  – matrix with raw data;  
 $W$  – matrix with reference answers;

**Result:**  
 $B_{1L}, B_{2L}, B_{3L}$  – vectors, with associated values of the fitness function; the determined optimal classifiers parameters; and the selected features;  
 $CF$  – confusion matrix with SMV classifier answers from  $3^{rd}$  layer;  
 $E$  – vector with the calculated evaluation coefficients of SVM classifier from  $3^{rd}$  layer;

```

1 for  $a \leftarrow 1$  to 3 (normalization types) do /* Normalization
  */
2   Perform signal pre-processing with normalization (no
  normalization or rescaling or standardization; Section
  2.3.1) based on  $X$ 
3   for  $b \leftarrow 1$  to 4 (window widths) do /* Feature
  extraction */
4     Perform feature extraction (Hamming window
  widths: 128 or 256 or 512 or 1024 samples; Section
  2.3.2)
5     Create training and testing sets and reference
  matrices based on  $W$  and stratified 10-fold CV
  method
6     for  $c \leftarrow 1$  to 4 (classifiers types) do /* 1st layer
  */
7       Set the values of the basic parameters of the
  classifier (SVM or kNN or PNN or RBFNN;
  Section 2.3.5 Table 2)
8       Set GA parameters (Section 2.3.6; Table 2)
9       Create an initial population /* Begin
  of GA */
10      for  $i \leftarrow 1$  to 30 (number of generations) do
11        for  $j \leftarrow 1$  to 50 (number of individuals)
12        do
13          Perform feature selection (Section
14          2.3.3) /* Feature selection
15          */
16          Set the value of the optimized
17          parameters of the classifier.
18          for  $k \leftarrow 1$  to 10 (no. of sets; Section
19          2.3.4) do
20            /* CV */
21            Create the model of the classifier
22            Determine the classifier answers
23            Determine the number of errors
24          end
25          Calculate the sum of errors for the
26          training and testing sets
27          Determine the value of the fitness
28          function ( $f_p$ )
29          Save the related values  $B_{1L}$  for the
30          fitness function ( $f_p$ ), classifier
31          parameters and selected features as
32          well as the matrices with classifier
33          answers:  $RL_{1L}$  and  $RT_{1L}$ 
34        end
35        if  $f_p == 0$  then
36          Lead out the “best” individual with
37          the corresponding answer matrices
38          break
39        else
40          Perform the selection of individuals
41          Apply the genetic operators: crossover
42          and mutation
43          Create a new population of individuals
44        end
45      end
46    end
47  end
48  ( /* End of GA */) Lead out the “best”
49  individual with the corresponding answer
50  matrices
51  Create the confusion matrix  $CF_{1L}$ 
52  Calculate the evaluation coefficients  $E_{1L}$  for
53  the classifier
54 end
55 end

```

---

**Algorithm 2: DGEC - Part II.**


---

```

38 Transform 1-output answers:  $RL_{1L}$  and  $RT_{1L}$  (for 24 SVM
  and kNN classifiers) on 17-output answers:  $R17_{1L}$ 
  /* 2nd layer */
39 Create training and testing sets based on  $R17_{1L}$  and
  stratified 10-fold CV method
40 for  $z \leftarrow 1$  to 4 (number of classifiers) do
41   Set the values of the basic parameters of the SVM
  classifier.
42   Set GA parameters (Table 3)
43   Create an initial population of individuals
  /* Begin of GA */
44   for  $i \leftarrow 1$  to 100 (number of generations) do
45     for  $j \leftarrow 1$  to 200 (number of individuals) do
46       Perform classifier selection /* Feature
  selection */
47       for  $k \leftarrow 1$  to 10 (number of sets) do /* CV */
48         Create the model of the SVM classifier
49         Determine the SVM classifier answers
50         Determine the number of errors
51       end
52       Calculate the sum of the errors for the training
  and testing sets
53       Determine the value of the fitness function ( $f_p$ )
54       Save the related values  $B_{2L}$  for the fitness
  function ( $f_p$ ) and selected features as well as
  the matrices with classifier answers:  $RL_{2L}$  and
   $RT_{2L}$ 
55     end
56     if  $f_p == 0$  then
57       Lead out the “best” individual with the answer
  matrices
58       break
59     else
60       Perform the selection of individuals
61       Apply the genetic operators: crossover and
  mutation
62       Create a new population of individuals
63     end
64   end
65   ( /* End of GA */) Lead out the “best” individual
  with the corresponding answer matrices
66   Create the confusion matrix  $CF_{2L}$ 
67   Calculate the evaluation coefficients  $E_{2L}$  for the SVM
  classifier
68 end
69 Transform 1-output answers:  $RL_{2L}$  and  $RT_{2L}$  (4 SVM
  classifiers) on 17-output answers:  $R17_{2L}$ 
  /* 3rd layer */
70 Create training and testing sets based on  $R17_{2L}$  and
  stratified 10-fold CV
71 Set the value of the basic parameters of the SVM classifier.
72 Set GA parameters (Table 3)
73 Create an initial population of individuals
  /* Begin of GA */
74 for  $i \leftarrow 1$  to 100 (number of generations) do
75   for  $j \leftarrow 1$  to 100 (number of individuals) do
76     Perform feature selection /* Feature
  selection */
77     for  $k \leftarrow 1$  to 10 (number of sets) do /* CV */
78       Create the model of the SVM classifier
79       Determine the SVM classifier answers
80       Determine the number of errors
81     end
82     Calculate the sum of the errors for the training and
  testing sets
83     Determine the value of the fitness function ( $f_p$ )
84     Save the related values  $B_{3L}$  for the fitness
  function ( $f_p$ ), selected features and the matrices with
  classifier answers:  $RL_{3L}$  and  $RT_{3L}$ 
85   end
86   if  $f_p == 0$  then
87     Lead out the “best” individual with the answer
  matrices
88     break
89   else
90     Perform the selection of individuals
91     Apply the genetic operators: crossover and mutation
92     Create a new population of individuals
93   end
94 end
95 ( /* End of GA */) Lead out the “best” individual with the
  corresponding answer matrices
96 Create the confusion matrix  $CF$ 
97 Calculate the evaluation coefficients  $E$  for the SVM classifier

```

---

## 2.5 Evaluation criteria

The following coefficients have been determined for the evaluation of the designed methods [30, 65]: (1) sum of errors for 744 classifications ( $ERR_{sum}$ ), (2) accuracy ( $ACC$ ), (3) specificity ( $SPE$ ), (4) sensitivity ( $SEN$ ) = overall accuracy ( $Acc$ ), (5) false positive rate ( $FPR$ ), (6) positive predictive value ( $PPV$ ), (7)  $\kappa$  coefficient, (8) time of optimization ( $T_o$ ), (9) time of training ( $T_t$ ), (10) time of classification ( $T_c$ ), and (11) acceptance feature coefficient ( $C_F$ ). Based on the *confusion matrices* generated, mentioned coefficients were calculated using values:  $TN$ —True Negative,  $TP$ —True Positive,  $FN$ —False Negative,  $FP$ —False Positive. More detailed information about the calculated coefficients can be found in the articles [51, 52].

The equations for the calculated coefficients are as follows:

- **Accuracy**

$$ACC = \left( \sum_{i=1}^N \frac{TP + TN}{TP + FP + TN + FN} \right) \cdot 100\% / N \quad (2)$$

- **Sensitivity = Overall Accuracy**

$$SEN = Acc = \left( \sum_{i=1}^N \frac{TP}{TP + FN} \right) \cdot 100\% / N \quad (3)$$

- **Specificity**

$$SPE = \left( \sum_{i=1}^N \frac{TN}{FP + TN} \right) \cdot 100\% / N \quad (4)$$

- **Positive Predictive Value**

$$PPV = \left( \sum_{i=1}^N \frac{TP}{TP + FP} \right) \cdot 100\% / N \quad (5)$$

- **False Positive Rate**

$$FPR = \left( \sum_{i=1}^N \frac{FP}{FP + TN} \right) \cdot 100\% / N \quad (6)$$

- **$\kappa$  coefficient (Fleiss' kappa)**

$$\kappa = \left( \sum_{i=1}^N \frac{M \sum_{k=1}^n m_{k,k} - \sum_{k=1}^n (G_k C_k)}{M^2 - \sum_{k=1}^n (G_k C_k)} \right) \cdot 100\% / N \quad (7)$$

where  $N$  is number of sets applied in the stratified tenfold CV method = 10,  $k$  is index of class,  $n$  equal to 17 is a number of classes,  $M$  is total number of classified ECG signal segments that are compared to the reference responses (labels),  $m_{k,k}$  is the number of

classified ECG signal segments belonging to the reference class  $k$  that have also been classified as a class  $j$ ,  $C_k$  is total number of classified ECG signal segments belonging to class  $k$ , and  $G_k$  is total number of reference responses (labels) belonging to class  $k$ .

- **Acceptance feature coefficient** (the smaller the better.)

$$C_F = \frac{F_a}{F} \cdot 100\% \quad (8)$$

where  $F_a$ —the number of accepted features, and  $F$ —the number of all features. More information about evaluation criteria can be found in the articles [51, 52].

## 3 Results

The MATLAB R2014b software along with the LIBSVM library was used in the work. The computer with an Intel Core i7-6700K 4.0 GHz (only one core was used) with 32 GB of RAM for calculations was used. All calculation times, including optimization, training, and testing stages, are presented in Tables 4, 5, and 6, respectively.

We have achieved sensitivity ( $SEN$ ) of 100% and  $ERR_{sum}$  equal to 0 errors for all training sets.

A comparison of achieved outcomes, for the ensembles of classifiers: CEC, DGEC, and single classifiers: SVM, PNN, RBFNN, kNN, is presented in Table 4.

### 3.1 Deep genetic ensemble of classifiers

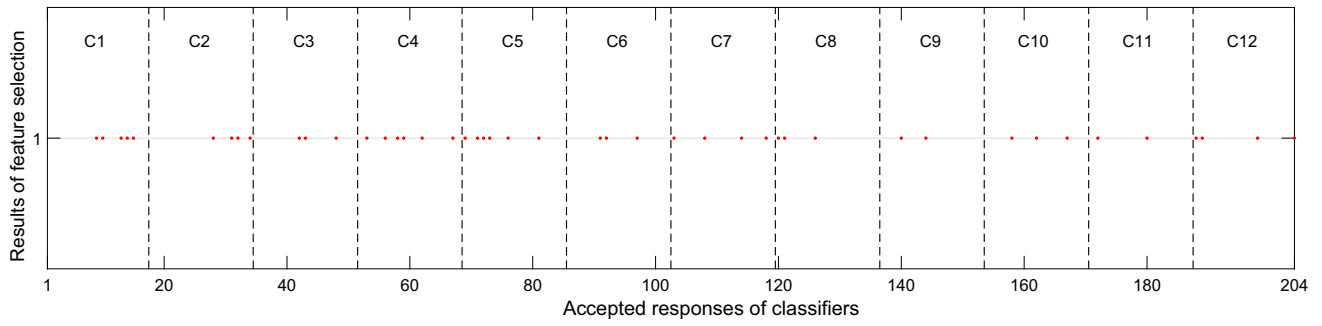
#### 3.1.1 First layer

Table 5 presents detailed results, for the first layer of DGEC system for four classifiers (RBFNN, PNN, kNN, and SVM) with values of optimized parameters for: (a) three signal preprocessing types (no normalization, rescaling + constant component reduction, and standardization), (b) four feature extraction types (four Hamming window widths 1024, 512, 256, and 128 samples), and (c) one CV variant—stratified tenfold.

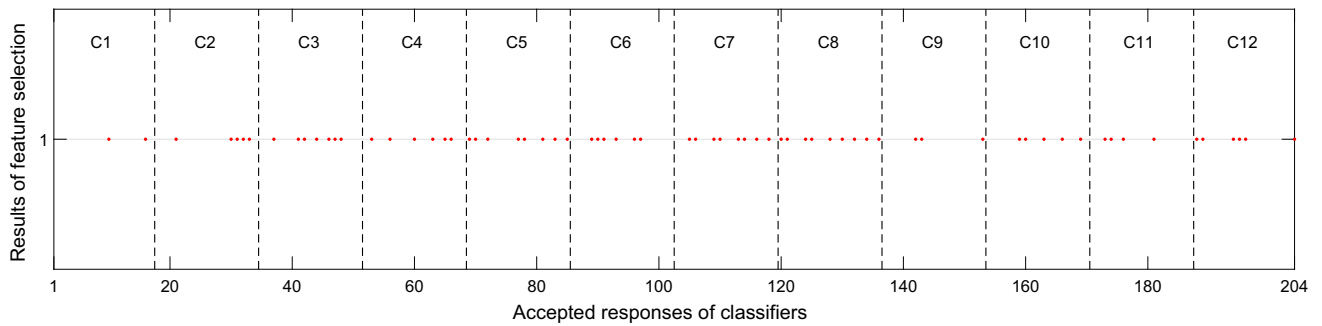
#### 3.1.2 Second layer

Optimized parameter values and outcomes for the second layer (4 C-SVC linear, SVM classifiers) and third layer (1 C-SVC linear SVM classifier) of the DGEC system are presented in Table 6.  $ERR_L$  coefficient determines in all training sets sum of errors.

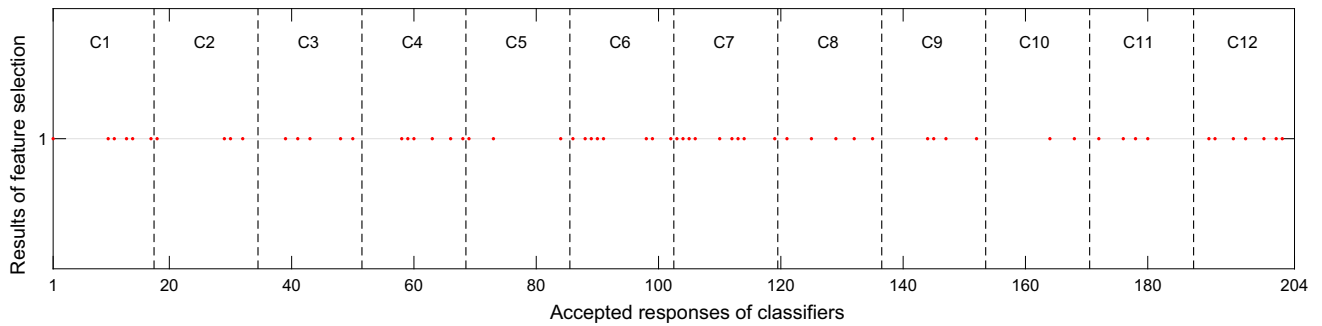
Figures 6, 7, 8, and 9 present the outcome visualizations of selection of features (*genetic layered training*), for the second layer of DGEC system. Accepted features (classifier answers) are shown by red dots. The votes (answers) of



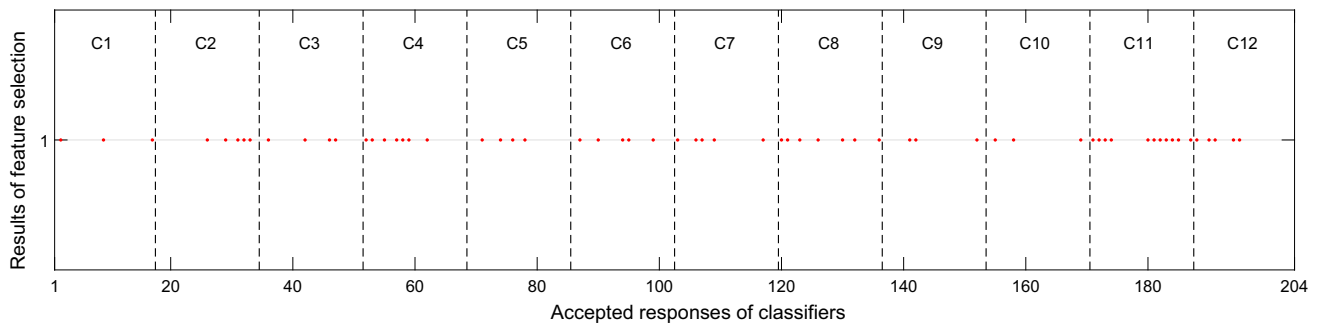
**Fig. 6** Selection of features (*genetic layered training*) outcomes for  $SVM_{49}$  (SVM) classifier from the second layer of DGEC method—in red accepted classifier answers (votes of experts)



**Fig. 7** Selection of features (*genetic layered training*) outcomes for  $SVM_{50}$  (kNN) classifier from the second layer of DGEC method—in red accepted classifier answers (votes of experts)



**Fig. 8** Selection of features (*genetic layered training*) outcomes for  $SVM_{51}$  (PNN) classifier from the second layer of DGEC method—in red accepted classifier answers (votes of experts)



**Fig. 9** Selection of features (*genetic layered training*) outcomes for  $SVM_{52}$  (RBFNN) classifier from the second layer of DGEC method—in red accepted classifier answers (votes of experts)

the 12 classifiers (experts) from the first layer were separated by a dashed black line. Figure 6 presents the answers of 12 SVM classifiers from the first layer, kNN in Fig. 7, PNN in Fig. 8, and RBFNN in Fig. 9.

### 3.1.3 Third layer

In Figs. 10, 11, 12, 14 and in Table 7, the results for entire DGEC system are presented.

In Fig. 10, the confusion matrix, for one SVM classifier from the third layer, is presented.

Figure 11 presents comparison of the following coefficients: sum of errors (*ERR*), accuracy (*ACC*), sensitivity (*SEN*), positive predictive value (*PPV*), specificity (*SPE*), false positive rate (*FPR*), and  $\kappa$  coefficient, for three variants of recognition (17, 15, and 12 classes).

In Fig. 12, percent error values for particular testing sets, from stratified tenfold CV method, for DGEC system, are presented.

Figure 13 presents the visualization of feature selection outcome (*genetic layered training*), for the third layer of DGEC system (one SVM classifier). Accepted features (answers of classifiers) are shown by red dots. The votes (answers) of the four SVMs (experts) from the second layer were separated by a dashed black line.

Table 7 indicates the detailed information on the efficiency of recognition for 17 ECG signal classes of the DGEC system. Coefficient *ERR*<sub>%</sub> indicates the percentage of errors.

In Fig. 14, *ERR*, *ACC*, *SEN*, *PPV*, *SPE*, and *FPR* for each class, are presented.

It can be seen from Table 8 that we have obtained the highest classification performance using the same database for the classification of 17 ECG classes.

## 4 Discussion

### 4.1 Hypothesis

Achieved outcomes confirmed the hypothesis that the use of designed new *DGEC system* is effective, automatic, fast, computationally less complex and universal classification of myocardium dysfunctions using ECG signals.

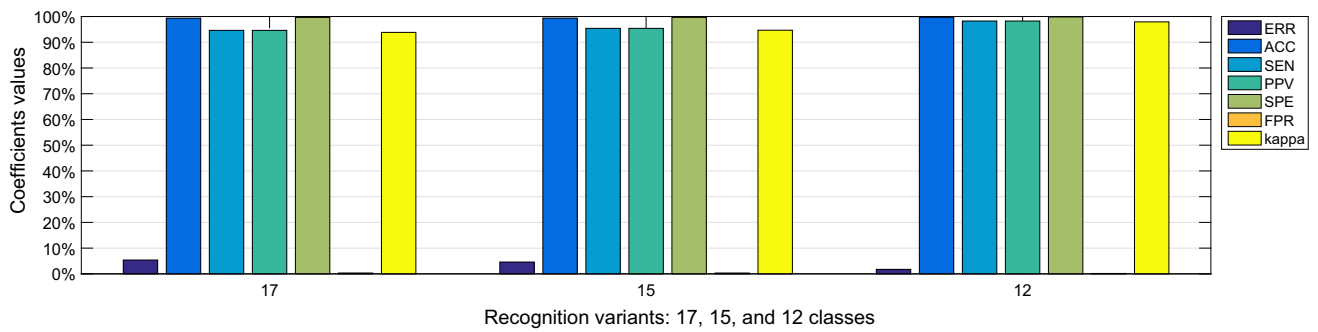
Tables 4 and 8 show the results obtained by our novel method. Our proposed method obtained the *SEN* = 94.62% (*ACC* = 99.37%, *SPE* = 99.66%).

We have obtained the highest classification performance (Table 8). It should be emphasized that we have classified 17 classes, the classification sensitivity for 15 classes = 95% and 12 classes = 98% (Fig. 11). Most of the other works from the literature present the results of the classification only for five classes.

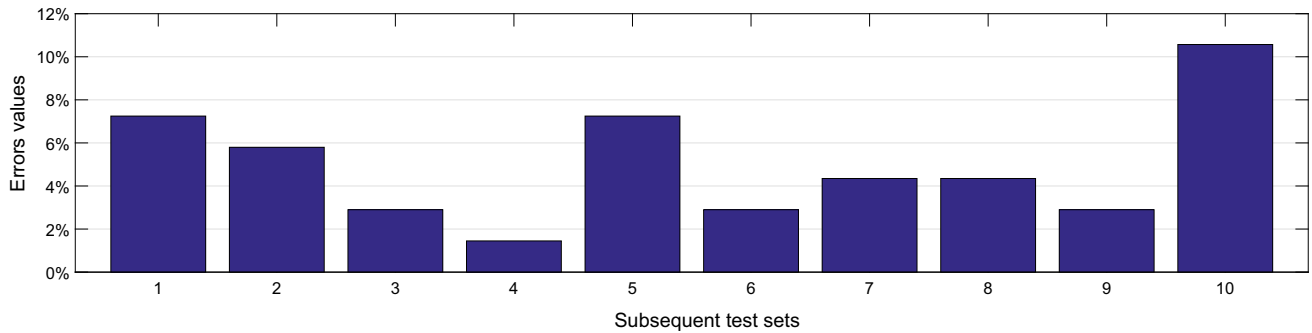
In this work, we have used a single (10-s) ECG signal segment and the time required to test the ECG signal is only  $C_k = 0.8736$  (s) for DGEC system. Hence, the developed system can be applied in telemedicine, cloud

Output class	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	
1	187 25.1%	10 1.3%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	3 0.4%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	1 0.1%	0 0.0%	1 0.1%	0 0.0%	0 0.0%	0 0.0%	92.6% 7.4%
2	5 0.7%	47 6.3%	0 0.0%	0 0.0%	2 0.3%	0 0.0%	1 0.1%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	1 0.1%	0 0.0%	0 0.0%	83.9% 16.1%
3	0 0.0%	0 0.0%	17 2.3%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	100% 0.0%
4	0 0.0%	1 0.1%	0 0.0%	92 12.4%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	98.9% 1.1%
5	0 0.0%	0 0.0%	0 0.0%	0 0.0%	8 1.1%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	100% 0.0%
6	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	21 2.8%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	100% 0.0%
7	1 0.1%	0 0.0%	0 0.0%	1 0.1%	1 0.1%	0 0.0%	67 9.0%	1 0.1%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	94.4% 5.6%
8	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	3 0.4%	42 5.6%	1 0.1%	2 0.3%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	87.5% 12.5%
9	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	1 0.1%	12 1.6%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	92.3% 7.7%
10	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	8 1.1%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	100% 0.0%
11	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	10 1.3%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	100% 0.0%
12	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	9 1.2%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	100% 0.0%
13	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	4 0.5%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	11 1.5%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	73.3% 26.7%
14	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	87 11.7%	0 0.0%	0 0.0%	0 0.0%	100% 0.0%
15	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	46 6.2%	0 0.0%	0 0.0%	100% 0.0%
16	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	10 1.3%	0 0.0%	100% 0.0%
17	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	30 4.0%	100% 0.0%
	96.9% 3.1%	81.0% 19.0%	100% 0.0%	98.9% 1.1%	72.7% 27.3%	100% 0.0%	85.9% 14.1%	95.5% 4.5%	92.3% 7.7%	80.0% 20.0%	100% 0.0%	90.0% 10.0%	100% 0.0%	98.9% 1.1%	97.9% 2.1%	100% 0.0%	100% 0.0%	94.6% 5.4%
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	

Fig. 10 Confusion matrix for *SVM*<sub>53</sub> classifier from the third layer of DGEC system



**Fig. 11** Comparison of coefficient values, for DGEC system, to recognize the variants of 17, 15, and 12 classes

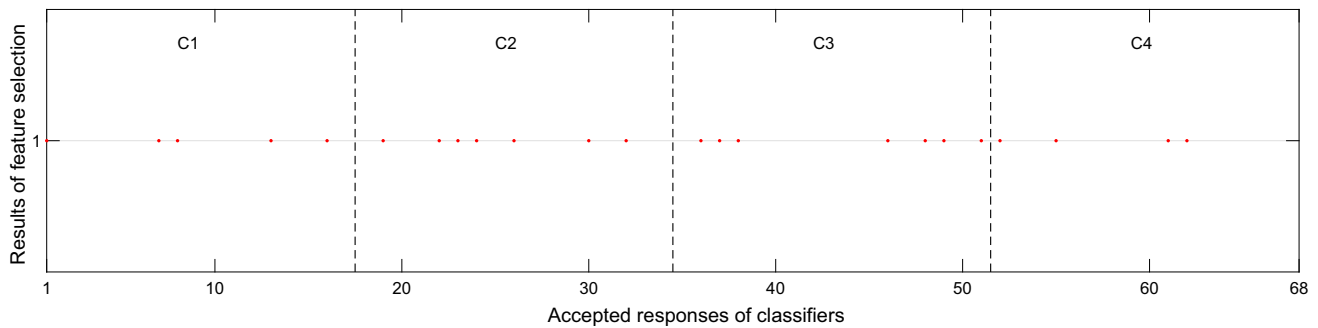


**Fig. 12** Error values for particular testing sets of DGEC system

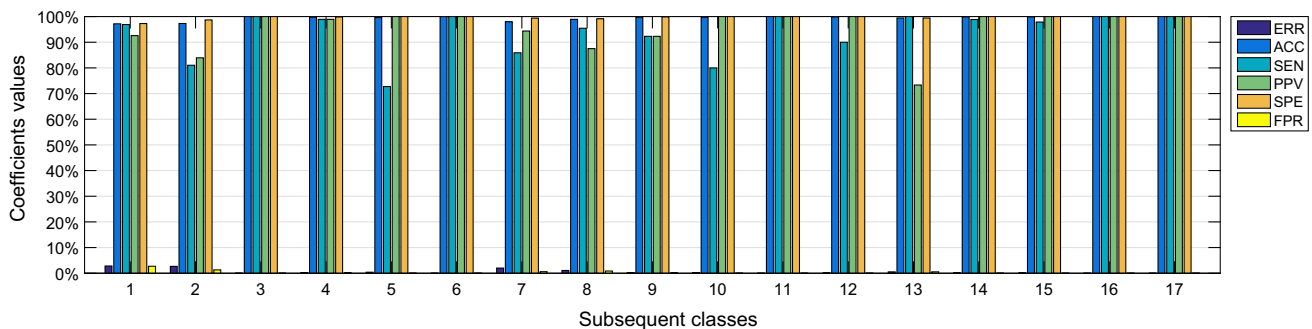
**Table 7** Coefficients of recognition for 17 ECG signal classes (heart disorders) with our DGEC system

Classes	Coefficients					
	<i>ERR</i> <sub>%</sub> (%)	ACC (%)	SEN (%)	SPE (%)	PPV (%)	FPR (%)
Normal sinus rhythm	2.82	97.18	96.89	97.28	92.57	2.72
Atrial premature beat	2.69	97.31	81.04	98.69	83.93	1.31
Atrial flutter	0.00	100.00	100.00	100.00	100.00	0.00
Atrial fibrillation	0.27	99.73	98.93	99.85	98.93	0.15
Supraventricular tachyarrhythmia	0.40	99.60	72.73	100.00	100.00	0.00
Pre-excitation (WPW)	0.00	100.00	100.00	100.00	100.00	0.00
Premature ventricular contraction	2.02	97.98	85.90	99.40	94.37	0.60
Ventricular bigeminy	1.08	98.93	95.46	99.14	87.50	0.86
Ventricular trigeminy	0.27	99.73	92.31	99.86	92.31	0.14
Ventricular tachycardia	0.27	99.73	80.00	100.00	100.00	0.00
Idioventricular rhythm	0.00	100.00	100.00	100.00	100.00	0.00
Ventricular flutter	0.13	99.87	90.00	100.00	100.00	0.00
Fusion of ventricular and normal beat	0.54	99.46	100.00	99.45	73.33	0.55
Left bundle branch block beat	0.13	99.87	98.86	100.00	100.00	0.00
Right bundle branch block beat	0.13	99.87	97.87	100.00	100.00	0.00
Second-degree heart block	0.00	100.00	100.00	100.00	100.00	0.00
Pacemaker rhythm	0.00	100.00	100.00	100.00	100.00	0.00

Coefficient *ERR*<sub>%</sub> indicates a percentage error



**Fig. 13** Selection of features (*genetic layered training*) outcomes for  $SVM_{53}$  classifier from the third layer of DGEC method—in red accepted classifier answers (votes of experts)



**Fig. 14** Comparison of coefficient values for all 17 classes

computing or mobile devices to aid the patients and clinicians to improve the accuracy of diagnosis.

## 4.2 Deep genetic ensemble of classifiers

Table 8 presents the results obtained using novel DGEC system, which confirm the validity of its design. The calculated coefficients for the DGEC system are:  $ERR_{sum} = 40$ ;  $SEN = 94, 62\%$ ;  $\kappa = 93, 84\%$ . These values are better than the results achieved using the CEC system:  $ERR_{sum} = 75$ ;  $SEN = 89, 92\%$ ;  $\kappa = 88, 38\%$  and are better than the best single classifier—SVM:  $ERR_{sum} = 73$ ;  $SEN = 90, 19\%$ ;  $\kappa = 88, 70\%$ .

Analyzing the outcomes from Tables 5 and 6, we understand that whole DGEC system achieved better result ( $EER_{sum} = 40$ ,  $SEN = 94, 62\%$ ) than the best component classifier from the first layer of DGEC system:  $EER_{sum} = 73$ ,  $SEN = 90.19\%$  or second layer of ensemble:  $EER_{sum} = 51$ ,  $SEN = 93.15\%$ . For all component classifiers from the first layer, the average result is  $EER_{sum} = 96.25$ ,  $SEN = 87.06\%$ .

It should be emphasized that the time of classification required for a single ECG signal segment (10-s) is only **0.8736** (s), although the whole ensemble is quite complex and consists of 53 classifiers.

## 4.3 Components of the classifier system

High performance of the DGEC system is presented in Tables 4, 5, 6, and Fig. 10. This result is obtained through: (1) appropriate connection of system nodes (classifiers) using genetic layered training in the second and third layer of the system, (2) diversity of the component classifiers (different classifiers make different errors) achieved by different signal normalization (three types), different Hamming window widths (four types), and different types of classifiers (four types), (3) adequate quality of the component classifiers of the system. Transformation of one output into 17 outputs of all component classifiers has enabled high performance of the genetic selection of votes (genetic layered training). Taking benefits from all component classifiers, and minimizing their drawbacks, was possible through combining classifiers using genetic feature selection.

## 4.4 Deep multilayer structure of the system

The success of designed DGEC system has been obtained based on: (1) genetic feature (frequency components) selection in the first layer of ensemble, (2) layered learning (accelerated and facilitated the training), (3) genetic layered training in the second and third layer (experts votes selection) applied to connection classifiers, (4) genetic



**Table 8** Comparison of work with other results obtained using the same database

Work	Year	# of classes	Feature set	Classifier	Acc = SEN (%)
Huang et al. [35]	2014	5	RR intervals, random projection	Ensemble of SVM	94
Llamedo and Martinez [41]	2011	5	Wavelet, VCG + SFFS	Weighted LD	93
Lin and Yang [40]	2014	5	Normalized RR-interval	Weighted LD	93
Bazi et al. [15]	2013	5	Morphological, wavelet	SVM, IWKLR, DTSVM	92
Soria and Martinez [66]	2009	5	morphological + FFS, VCG, RR-intervals	Weighted LD	90
Mar et al. [42]	2011	5	Statistical features + SFFS, morphological, temporal features	Weighted LD, MLP	89
Zhang and Luo [79]	2014	5	wavelet coeff., RR-intervals, ECG-inter. and segments, morph. features	Combined SVM	87
Zhang et al. [78]	2014	5	ECG-intervals and segments, morphological features, RR-intervals	Combined SVM	86
Ye et al. [74]	2012	5	ICA, RR interval, wavelet, PCA, morphological	SVM	86
Park et al. [49]	2008	5	HOS, HBF	Hierarchical SVM	85
de Lannoy et al. [26]	2012	5	HBF, morphological, ECG segments, HOS, RR intervals	Weighted CRF	85
de Chazal et al. [24]	2004	5	ECG-intervals, morphological	Weighted LD	83
de Lannoy et al. [25]	2010	5	HBF coefficients, ECG-Intervals, HOS, morphological	Weighted SVM	83
Martis et al. [43]	2012	5	Principal components of segmented ECG beats Principal components of error signals of linear prediction model Principal components of DWT	NN, LS-SVM	98
Elhaj et al. [29]	2016	5	HOS, cumulants, ICA, PCA, DWT	NN, SVM	99
Yang et al. [73]	2018	5	PCANet	Linear SVM	98
Zubair et al. [80]	2016	5	Raw data	CNN	93
Acharya et al. [6]	2017	5	Raw data	CNN	94
Yildirim [75]	2018	5	Raw data	DBLSTM-WS3	99
Plawiak [52]	2018	17	Frequency components of the PSD of ECG signal	Evolutionary Neural System (based on single SVM)	90
Plawiak [51]	2018	17	Frequency components of the PSD of ECG signal	Genetic Ensemble of Classifiers (two-layer system)	91
Yildirim et al. [77]	2018	17	Rescaling raw data	1D-CNN	91
Proposed method		12	Frequency components of the PSD of ECG signal	Deep genetic ensemble of classifiers (DGEC), three-layer system	98
		15			95
		17			95

parameters optimization (appropriate balance between exploitation and exploration) coupled with stratified ten-fold CV, which significantly decreased the over-training and hence increased the performance of the DGEC method, and (5) DL (multilayer structure of system, in which extraction of features and pattern recognition occur through appropriate flow and fusion of information).

#### 4.5 Deep learning

DGEC system based on DL. This section presents a comparison of the DGEC system with other DL algorithms such as the convolutional neural network (CNN).

**Advantages** of our system are given below:

- obtained higher accuracy (e.g. compared to work [77]).
- the possibility of greater interference in the optimization of the structure (selection of: nodes (classifiers), number of layers, connections between nodes, etc.).

**Disadvantages** of our method are given below:

- complex structure requiring longer system design (longer training and optimization).
- the feature extraction needs to be performed.

**Similarities** with other systems are as follows:

- also a network of neurons (nodes process information), consisting of nodes in the form of classifiers.
- also has a deep structure in which occur similar processes of fusion and flow information (with successive layers, the concepts are more and more abstract).

**Differences** with other state-of-art systems are as given below:

- nodes, these are not classic neurons (with weights, biases, and activation functions) but more complex classifiers and each node is different (greater diversity of nodes).
- outputs, instead of one there are 17 outputs from each node (classifier).
- training and optimization, performed in stages, one by one in subsequent layers, and the results from the previous layer go to the next layer, in the CNN training and optimization is more global.
- connections, flexibility in designing connections between nodes (classifiers) from different layers.
- structure, in the first layer, nodes (classifiers) are called *experts*, and in the second and third layer are called *judges*. In the first layer, a processed ECG signal is given to the inputs of nodes, and in the second and third layer on the nodes (classifiers) inputs are given votes (17 answers with values of “0” or “1” indicated the recognized class) of each of the classifiers from the first layer.
- structure tuning, eliminating incorrect voices (second and third layer), and ECG signal feature selection (first layer), and optimization of classifier (nodes) parameters is performed using GA.

#### 4.6 Dysfunctions/classes

Classification performance for all classes of DGEC system is presented in Fig. 14. We can notice from the results that *PPV* of **over 70%** and *SEN* of **over 70%** are achieved

despite using the imbalanced data, which is a significant success. The worst results have been achieved for *fusion of ventricular and normal beats* ( $PPV = 73.33\%$  and *supraventricular tachyarrhythmia*  $SEN = 72.73\%$ ), which is shown in Table 7.

Heart abnormalities with the smallest values of *PPV* and *SEN* coefficients have been removed, based on the achieved results as shown in Fig. 14. Two other classification variants have been analyzed: **12 classes** (after removing classes: *SVTA*, *PVC*, *TRI*, *VT*, and *FUS*, Table 1), and **15 classes** (after removing classes: *SVTA*, and *FUS*, Table 1). The DGEC system achieved the *SEN* for **12, 15, and 17 classes 98.25%, 95.40%, and 94.62%**, respectively, and  $\kappa = 97.92\%$ , **94.68%**, and **93.84%**, respectively.

## 5 Conclusion

The objective of this study was to develop new ML method, focusing on EC and also EL and DL approach which enables the effective classification of cardiac arrhythmias (17 classes: normal sinus rhythm, 15 types of arrhythmias and pacemaker rhythm) using ECG signal segments (10-s). Our main contribution is the design of a novel three-layer (48 + 4 + 1) genetic ensemble of classifiers. Novel system based on fusion of three normalization types, four Hamming window widths, four classifiers types, stratified tenfold CV, genetic feature (frequency components) selection, EL, layered learning, DL, EC, classifiers parameters optimization by GA, and new genetic layered training (expert votes selection) to connect the classifiers.

The **DGEC** system achieved a classification sensitivity of **17 cardiac arrhythmias (classes) equal to 94.62% (40 errors / 744 classifications, accuracy = 99.37%, specificity = 99.66%, classification time of single sample = 0.8736(s))**. To the best of our knowledge, this is the highest classification performance obtained for 17 ECG classes using 10 s ECG segments.

The salient features of our work are as follows: (1) **strong imbalanced data** for some classes, (2) classification of **17 classes** of cardiac disorders, and (3) application of **stratified tenfold CV method** (analogous to **subject-oriented validation scheme**).

The authors have designed a new DGEC system for the effective (Table 8), automatic, fast (Table 4), low computational complexity (Sect. 1) and universal (Table 1), classification of cardiac disorders.

The strengths of the research are: (1) possibility to use our solution in telemedicine and implement designed method in mobile devices or cloud computing (only single lead, lower computational complexity, and low cost), (2)

high performance, (3) classification of 17 heart disorders (classes), (4) design of new genetic layered training applied to connecting classifiers, and (5) design of novel ML method—DGEC system.

Due to the very promising results obtained, the described research is worth continuing. The next stages of research will include: (1) improving the accuracy of recognition myocardium dysfunctions through development and improving the algorithms based on fusion of EL and DL, (2) testing the other optimization methods based on EC, and (3) testing the efficiency of DGEC system with other physiologic signals.

**Acknowledgements** The authors thanks Prof. R. Tadeusiewicz, Prof. Z. Tabor, and Prof. J. Leśkow for their valuable advice and guidance on the preparation of this article.

## Compliance with ethical standards

**Conflict of interest** There is no conflict of interest in this work.

**Open Access** This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

## References

- Abdar M (2015) Using decision trees in data mining for predicting factors influencing of heart disease. *Carpathian J Electron Comput Eng* 8(2):31–36
- Abdar M, Yen NY, Hung JCS (2017) Improving the diagnosis of liver disease using multilayer perceptron neural network and boosted decision trees. *J Med Biol Eng*. <https://doi.org/10.1007/s40846-017-0360-z>
- Abdar M, Zomorodi-Moghadam M, Zhou X, Gururajan R, Tao X, Barua PD, Gururajan R (2018) A new nested ensemble technique for automated diagnosis of breast cancer. *Pattern Recognit Lett*. <http://www.sciencedirect.com/science/article/pii/S0167865518308766>. Accessed 3 Dec 2018
- Acharya UR, Fujita H, Lih OS, Hagiwara Y, Tan JH, Adam M (2017) Automated detection of arrhythmias using different intervals of tachycardia ECG segments with convolutional neural network. *Inf Sci* 405:81–90. <https://doi.org/10.1016/j.ins.2017.04.012>
- Acharya UR, Fujita H, Oh SL, Hagiwara Y, Tan JH, Adam M (2017) Application of deep convolutional neural network for automated detection of myocardial infarction using ECG signals. *Inf Sci* 415–416:190–198. <https://doi.org/10.1016/j.ins.2017.06.027>
- Acharya UR, Oh SL, Hagiwara Y, Tan JH, Adam M, Gertych A, Tan RS (2017) A deep convolutional neural network model to classify heartbeats. *Comput Biol Med* 89:389–396. <https://doi.org/10.1016/j.combiomed.2017.08.022>
- AHA (2003) International cardiovascular disease statistics. <https://www.bellevuecollege.edu/artshum/materials/inter/Spring04/SizeMatters/InternatCardioDisSTATsp04.pdf>. Accessed 19 June 2017
- AHA (2016) Heart disease, stroke and research statistics at-a-glance. [http://www.heart.org/idc/groups/ahamh-public/@wcm/@sop/@smd/documents/downloadable/ucm\\_480086.pdf](http://www.heart.org/idc/groups/ahamh-public/@wcm/@sop/@smd/documents/downloadable/ucm_480086.pdf). Accessed 19 June 2017
- Alkeshuosh AH, Moghadam MZ, Mansoori IA, Abdar M (2017) Using PSO algorithm for producing best rules in diagnosis of heart disease. In: 2017 international conference on computer and applications (ICCA), pp 306–311. <https://doi.org/10.1109/COMAPP.2017.8079784>
- Altman NS (1992) An introduction to kernel and nearest-neighbor nonparametric regression. *Am Stat* 46(3):175–185
- Arel I, Rose DC, Karnowski TP (2010) Deep machine learning—a new frontier in artificial intelligence research [research frontier]. *IEEE Comput Intell Mag* 5(4):13–18. <https://doi.org/10.1109/MCI.2010.938364>
- Augustyniak P, Tadeusiewicz R (2007) Web-based architecture for ECG interpretation service providing automated and manual diagnostics. *Biocybern Biomed Eng* 27(1/2):233–241. <https://doi.org/10.1.1.208.9247>
- Augustyniak P, Tadeusiewicz R (2009) Ubiquitous cardiology—emerging wireless telemedical application. In Augustyniak P, Tadeusiewicz R (eds) Chapter background 1: ECG interpretation: fundamentals of automatic analysis procedures, pp 11–71. IGI Global, Hershey. <https://doi.org/10.4018/978-1-60566-080-6.ch002>
- Back T, Hammel U, Schwefel HP (1997) Evolutionary computation: comments on the history and current state. *IEEE Trans Evol Comput* 1(1):3–17. <https://doi.org/10.1109/4235.585888>
- Bazi Y, Alajlan N, AlHichri H, Malek S (2013) Domain adaptation methods for ECG classification. In: 2013 international conference on computer medical applications (ICCA), pp 1–4. <https://doi.org/10.1109/ICCA.2013.6506156>
- Bengio Y (2009) Learning deep architectures for AI. *Found Trends Mach Learn* 2(1):1–127. <https://doi.org/10.1561/2200000006>
- Bengio Y, Courville A, Vincent P (2013) Representation learning: a review and new perspectives. *IEEE Trans Pattern Anal Mach Intell* 35(8):1798–1828. <https://doi.org/10.1109/TPAMI.2013.50>
- Broomhead DS, Lowe D (1988) Radial basis functions, multi-variable functional interpolation and adaptive networks. *Complex Syst* 2:321–355
- Chang CC, Lin CJ (2011) LIBSVM: a library for support vector machines. *ACM Trans Intell Syst Technol* 2:27:1–27:27
- Cortes C, Vapnik V (1995) Support-vector networks. *Mach Learn* 20(3):273–297. <https://doi.org/10.1007/BF00994018>
- Cruz RM, Sabourin R, Cavalcanti GD (2018) Dynamic classifier selection: recent advances and perspectives. *Inf Fusion* 41(Supplement C):195–216. <https://doi.org/10.1016/j.inffus.2017.09.010>
- da Luz EJS, Nunes TM, de Albuquerque VHC, Papa JP, Menotti D (2013) ECG arrhythmia classification based on optimum-path forest. *Expert Syst Appl* 40(9):3561–3573. <https://doi.org/10.1016/j.eswa.2012.12.063>
- da Luz EJS, Schwartz WR, Cámara-Chávez G, Menotti D (2016) ECG-based heartbeat classification for arrhythmia detection: a survey. *Comput Methods Prog Biomed* 127:144–164. <https://doi.org/10.1016/j.cmpb.2015.12.008>
- de Chazal P, O'Dwyer M, Reilly RB (2004) Automatic classification of heartbeats using ECG morphology and heartbeat interval features. *IEEE Trans Biomed Eng* 51(7):1196–1206. <https://doi.org/10.1109/TBME.2004.827359>
- de Lammoy G, Francois D, Delbeke J, Verleysen M (2010) Weighted SVMs and feature relevance assessment in supervised heart beat classification. In: Fred A, Filipe J, Gamboa H (eds)

- Communications in computer and information science, chapter biomedical engineering systems and technologies, vol 127. Springer, Berlin, pp 212–223. <https://doi.org/10.1007/978-3-642-18472-7>
26. de Lannoy G, Francois D, Delbeke J, Verleysen M (2012) Weighted conditional random fields for supervised interpatient heartbeat classification. *IEEE Trans Biomed Eng* 59(1):241–247. <https://doi.org/10.1109/TBME.2011.2171037>
  27. Deng L, Yu D (2014) Deep learning: methods and applications. *Found Trends Signal Process* 7:197–387. <https://doi.org/10.1561/20000000039>
  28. Derrac J, Garcia S, Molina D, Herrera F (2011) A practical tutorial on the use of nonparametric statistical tests as a methodology for comparing evolutionary and swarm intelligence algorithms. *Swarm Evol Comput* 1(1):3–18. <https://doi.org/10.1016/j.swevo.2011.02.002>
  29. Elhaj FA, Salim N, Harris AR, Swee TT, Ahmed T (2016) Arrhythmia recognition and classification using combined linear and nonlinear features of ECG signals. *Comput Methods Prog Biomed* 127:52–63. <https://doi.org/10.1016/j.cmpb.2015.12.024>
  30. Fawcett T (2006) An introduction to ROC analysis. *Pattern Recogn Lett* 27(8):861–874. <https://doi.org/10.1016/j.patrec.2005.10.010>
  31. Goldberger AL, Amaral LAN, Glass L, Hausdorff JM, Ivanov PC, Mark RG, Mietus JE, Moody GB, Peng CK, Stanley HE (2000) PhysioBank, PhysioToolkit, and PhysioNet: components of a new research resource for complex physiologic signals. *Circulation* 101(23):e215–e220. <https://doi.org/10.1161/01.CIR.101.23.e215>
  32. Goodfellow I, Bengio Y, Courville (2016) A deep learning. <http://www.deeplearningbook.org>. Book in preparation for MIT Press. Accessed 19 June 2017
  33. Healthsquare (2007) Heart disease. In: Conference on computational intelligence for modelling control and automation, pp 179–182. <http://www.healthsquare.com/heartdisease.htm>. Accessed 19 June 2017
  34. Heron MP, Smith BL (eds) (2003) Deaths: leading causes for 2003. National Center for Health Statistics, Hyattsville
  35. Huang H, Liu J, Zhu Q, Wang R, Hu G (2014) A new hierarchical method for inter-patient heartbeat classification using random projections and RR intervals. *Biomed Eng* 13:1–26
  36. Kennedy J, Eberhart R (1995) Particle swarm optimization. In: Proceedings of the IEEE international conference on neural networks, vol 4, pp 1942–1948. <https://doi.org/10.1109/ICNN.1995.488968>
  37. Krawczyk B, Minku LL, Gama J, Stefanowski J, Woźniak M (2017) Ensemble learning for data stream analysis: a survey. *Inf Fusion* 37(Supplement C):132–156. <https://doi.org/10.1016/j.inffus.2017.02.004>
  38. Kuncheva LI (2004) Combining pattern classifiers: methods and algorithms. Wiley-Interscience, New York
  39. LeCun Y, Bengio Y, Hinton G (2015) Deep learning. *Nature* 521:436–444
  40. Lin CC, Yang CM (2014) Heartbeat classification using normalized RR intervals and wavelet features. In: 2014 international symposium on computer, consumer and control (IS3C), pp 650–653. <https://doi.org/10.1109/IS3C.2014.175>
  41. Llamedo M, Martinez JP (2011) Heartbeat classification using feature selection driven by database generalization criteria. *IEEE Trans Biomed Eng* 58(3):616–625. <https://doi.org/10.1109/TBME.2010.2068048>
  42. Mar T, Zaunseder S, Martinez JP, Llamedo M, Poll R (2011) Optimization of ECG classification by means of feature selection. *IEEE Trans Biomed Eng* 58(8):2168–2177. <https://doi.org/10.1109/TBME.2011.2113395>
  43. Martis RJ, Acharya UR, Mandana K, Ray A, Chakraborty C (2012) Application of principal component analysis to ECG signals for automated diagnosis of cardiac health. *Expert Syst Appl* 39(14):11792–11800. <https://doi.org/10.1016/j.eswa.2012.04.072>
  44. McLachlan GJ (2004) Discriminant analysis and statistical pattern recognition (Wiley series in probability and statistics). Wiley, New York. <http://www.amazon.com/exec/obidos/redirect?tag=citeulike07-20&path=ASIN/0471691151>. Accessed 19 June 2017
  45. Moody GB, Mark RG (2001) The impact of the MIT-BIH arrhythmia database. *IEEE Eng Med Biol Mag* 20(3):45–50. <https://doi.org/10.1109/51.932724>
  46. Naik GR, Selvan SE, Arjunan SP, Acharyya A, Kumar DK, Ramanujam A, Nguyen HT (2018) An ICA-EBM-based sEMG classifier for recognizing lower limb movements in individuals with and without knee pathology. *IEEE Trans Neural Syst Rehabil Eng* 26(3):675–686. <https://doi.org/10.1109/TNSRE.2018.2796070>
  47. Oza NC, Tumer K (2008) Classifier ensembles: select real-world applications. *Inf Fusion* 9(1):4–20. <https://doi.org/10.1016/j.inffus.2007.07.002> (Special Issue on Applications of Ensemble Methods)
  48. Padmavathi K, Ramakrishna KS (2015) Classification of ECG signal during Atrial fibrillation using autoregressive modeling. *Procedia Comput Sci* 46:53–59. <https://doi.org/10.1016/j.procs.2015.01.053>. Proceedings of the International Conference on Information and Communication Technologies, ICICT 2014, 3–5 December 2014 at Bolgatty Palace& Island Resort, Kochi, India)
  49. Park KS, Cho BH, Lee DH, Song SH, Lee JS, Chee YJ, Kim IY, Kim SI (2008) Hierarchical support vector machine based heartbeat classification using higher order statistics and hermite basis function. *Comput Cardiol* 2008:229–232. <https://doi.org/10.1109/CIC.2008.4749019>
  50. Plawiak P (2014) An estimation of the state of consumption of a positive displacement pump based on dynamic pressure or vibrations using neural networks. *Neurocomputing* 144:471–483. <https://doi.org/10.1016/j.neucom.2014.04.026>
  51. Plawiak P (2018) Novel genetic ensembles of classifiers applied to myocardium dysfunction recognition based on ECG signals. *Swarm Evol Comput* 39:192–208. <https://doi.org/10.1016/j.swevo.2017.10.002>
  52. Plawiak P (2018) Novel methodology of cardiac health recognition based on ECG signals and evolutionary-neural system. *Expert Syst Appl* 92:334–349. <https://doi.org/10.1016/j.eswa.2017.09.022>
  53. Plawiak P, Maziarz W (2014) Classification of tea specimens using novel hybrid artificial intelligence methods. *Sensors Actuators B Chem* 192:117–125. <https://doi.org/10.1016/j.snb.2013.10.065>
  54. Plawiak P, Rzecki K (2015) Approximation of phenol concentration using computational intelligence methods based on signals from the metal-oxide sensor array. *IEEE Sensors J* 15(3):1770–1783. <https://doi.org/10.1109/JSEN.2014.2366432>
  55. Prieto A, Prieto B, Ortigosa EM, Ros E, Pelayo F, Ortega J, Rojas I (2016) Neural networks: an overview of early research, current frameworks and new challenges. *Neurocomputing* 214:242–268. <https://doi.org/10.1016/j.neucom.2016.06.014>
  56. Quinlan J (1986) Induction of decision trees. *Mach Learn* 1(1):81–106. <https://doi.org/10.1023/A:1022643204877>
  57. Rajesh KN, Dhuli R (2017) Classification of ECG heartbeats using nonlinear decomposition methods and support vector machine. *Comput Biol Med* 87:271–284. <https://doi.org/10.1016/j.combiomed.2017.06.006>
  58. Rajesh KN, Dhuli R (2018) Classification of imbalanced ECG beats using re-sampling techniques and adaboost ensemble



- classifier. *Biomed Signal Process Control* 41:242–254. <https://doi.org/10.1016/j.bspc.2017.12.004>
59. Rutkowski L (2008) Computational intelligence: methods and techniques. Springer, Berlin
60. Rzecki K, Pławiak P, Niedźwiecki M, Sośnicki T, Leśkow J, Ciesielski M (2017) Person recognition based on touch screen gestures using computational intelligence methods. *Inf Sci* 415–416:70–84. <https://doi.org/10.1016/j.ins.2017.05.041>
61. Rzecki K, Sośnicki T, Baran M, Niedźwiecki M, Król M, Łojewski T, Acharya U, Yildirim O, Pławiak P (2018) Application of computational intelligence methods for the automated identification of paper-ink samples based on libs. *Sensors* 18(11):3670. <https://doi.org/10.3390/s18113670>
62. Santos EMD, Sabourin R, Maupin P (2009) Overfitting cautious selection of classifier ensembles with genetic algorithms. *Inf Fusion* 10(2):150–162. <https://doi.org/10.1016/j.inffus.2008.11.003>
63. Schmidhuber J (2015) Deep learning in neural networks: an overview. *Neural Netw* 61:85–117. <https://doi.org/10.1016/j.neunet.2014.09.003>
64. Smith S (2002) Digital signal processing: a practical guide for engineers and scientists. Newnes, Oxford
65. Sokolova M, Lapalme G (2009) A systematic analysis of performance measures for classification tasks. *Inf Process Manag* 45(4):427–437. <https://doi.org/10.1016/j.ipm.2009.03.002>
66. Soria ML, Martinez J (2009) Analysis of multidomain features for ECG classification. *Comput Cardiol* 2009:561–564
67. Specht DF (1990) Probabilistic neural networks. *Neural Netw* 3(1):109–118
68. National Center for Health Statistics (ed.) (2005) Health, United States, 2005 with chartbook on the health of Americans. National Center for Health Statistics, Hyattsville
69. Sugeno M (1985) Industrial applications of fuzzy control. Elsevier Science Pub. Co., Amsterdam
70. Welch P (1967) The use of fast Fourier transform for the estimation of power spectra: a method based on time averaging over short, modified periodograms. *IEEE Trans Audio Electroacoust* 15(2):70–73. <https://doi.org/10.1109/TAU.1967.1161901>
71. WHO (2014) WHO global status report on noncommunicable diseases. [http://apps.who.int/iris/bitstream/10665/148114/1/9789241564854\\_eng.pdf?ua=1](http://apps.who.int/iris/bitstream/10665/148114/1/9789241564854_eng.pdf?ua=1). Accessed 19 June 2017
72. Woźniak M, Grana M, Corchado E (2014) A survey of multiple classifier systems as hybrid systems. *Inf Fusion* 16(Supplement C):3–17. <https://doi.org/10.1016/j.inffus.2013.04.006>. (Special Issue on Information Fusion in Hybrid Intelligent Fusion Systems)
73. Yang W, Si Y, Wang D, Guo B (2018) Automatic recognition of arrhythmia based on principal component analysis network and linear support vector machine. *Comput Biol Med* 101:22–32. <https://doi.org/10.1016/j.compbimed.2018.08.003>
74. Ye C, Kumar BVKV, Coimbra MT (2012) Combining general multi-class and specific two-class classifiers for improved customized ECG heartbeat classification. In: 2012 21st international conference on pattern recognition (ICPR), pp 2428–2431
75. Yildirim O (2018) A novel wavelet sequences based on deep bidirectional LSTM network model for ECG signal classification. *Comput Biol Med* 96:189–202. <https://doi.org/10.1016/j.compbimed.2018.03.016>
76. Yildirim Ö, Baloglu UB, Acharya UR (2018) A deep convolutional neural network model for automated identification of abnormal EEG signals. *Neural Comput Appl*. <https://doi.org/10.1007/s00521-018-3889-z>
77. Yildirim O, Pławiak P, Tan RS, Acharya UR (2018) Arrhythmia detection using deep convolutional neural network with long duration ECG signals. *Comput Biol Med* 102:411–420. <https://doi.org/10.1016/j.compbimed.2018.09.009>
78. Zhang Z, Dong J, Luo X, Choi KS, Wu X (2014) Heartbeat classification using disease-specific feature selection. *Comput Biol Med* 46:79–89. <https://doi.org/10.1016/j.compbimed.2013.11.019>
79. Zhang Z, Luo X (2014) Heartbeat classification using decision level fusion. *Biomed Eng Lett* 4(4):388–395. <https://doi.org/10.1007/s13534-014-0158-7>
80. Zubair M, Kim J, Yoon C (2016) An automated ECG beat classification system using convolutional neural networks. In: 2016 6th international conference on IT convergence and security (ICITCS), pp 1–5. <https://doi.org/10.1109/ICITCS.2016.7740310>