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NEW APPLICATIONS OF ARTIFICIAL NEURAL NETWORKS IN MODELING & CONTROL

A survey of software and hardware use in artificial neural networks

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Abstract Artificial neural networks (ANNs) have been widely used over the last three decades. During this period, many hardware and software solutions have been developed and today a new user entering the field can make a fast trial to this artificial intelligence solution with commercial software and hardware, instead of developing a solution from scratch thus saving a lot of time. This work aims at helping new and experienced users even further by sharing the ANNs experience in software and hardware collected. This was achieved through a survey questionnaire about present and past used solutions of software and hardware, as well as future prospects for the development of application areas. To further enlighten the reader, a logistic regression (LR) statistical analysis is performed on the obtained results to extract additional details about the answers obtained from the ANN community. The LR statistical analysis verifies whether the researchers with more than 25 years of experience in ANNs use self-written code when compared to those with less years of experience in the area. The LR statistical analysis also verifies whether researchers with less than 25 years of experience in ANNs use some platform to develop their hardware when compared to those who have more years of experience.

Keywords Artificial neural networks · Neural network hardware · Neural network software

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1 Introduction

Artificial neural networks (ANNs) have been widely used over three decades. In the very beginning, researchers were obliged to build their own software to implement the neural models and eventually build specific hardware to meet their needs.

Nowadays, there are many software and hardware solutions available on the market. Naturally, some of these solutions have proved to be more reliable or more fitted to a specific class of models within the ANN world.

One of the earliest commercial software used in ANN research, named parallel distributed processing (PDP), became popular in 1986 [1]. Since then, ANN software development has evolved over time, and currently, there are several options to choose from. Table 1 shows the chronology of the various types of commercial software used in ANN research.

It is important to point out that Emergent is the direct descendent of PDP and PDP++, and SYNOD is the direct descendent of NEST.

Hardware may also be used to implement ANNs. Most of the ANN implementations are done with a personal computer (PC). However, PCs are bulky, heavy, and expensive.

In the mid-1980s, the application-specific integrated circuits (ASIC) became widespread, and significant work in the design and ANN implementation of hardware was made. Nevertheless, most of these efforts were not successful because at the time, the need for hardware in ANN was not in demand and neither was the development of the electronics support [11, 12].

In the 1990s, a new type of processor, named field programmable gate array (FPGA), became very well known. The FPGA allows programmers to reconfigure the

Table 1 Chronology of the various types of commercial software used in ANN research

Tool name	Year of development
Parallel distributed processing (PDP) [1]	1986
General NEural SImulation System (GENESIS) [2]	1988
NEURON simulation tool [3]	1990
Neural Network toolbox for MatLab [4, 5]	1990
SYNOD neural network simulator [6]	1994
Parallel distributed processing++ (PDP++) [1]	1999
NEST simulation software [7]	2001
EMERGENT neural simulation software [8]	2007
Neural network library using THEANO [9]	2008
NEUROPH object-oriented neural network framework [10]	2008

hardware connections within it between arrays of digital electronic logic gates which presents a more realistic alternative of the ANNs, and consequently, ANN-based FPGAs are now a more practical proposition than they have been in the past [13–15].

Many applications are being implemented with dedicated hardware, some using ASICs [16] and others using FPGAs [13–17].

The need to abandon the most common implementation of ANN with a PC might arise from a number of reasons: reducing the cost of the implementation, achieving higher processing speed, or simpler implementations [14].

Since there are ANN researchers that initiated their work before commercial ANN software became widely popular in the mid-1980s, we were motivated to know whether these researchers continued to use self-written code. With this said, we believe that most researchers with more than 25 years of experience, in ANN research, use their own developed software.

In regard to hardware use in ANN research, we know that commercial ASIC hardware became popular in the mid-1980s so we were motivated to know whether only the researchers with less than 25 years of experience used the ASIC and FPGA to develop their hardware in ANN research.

Based on this information, the first research hypothesis used in this paper is as follows: "Researchers with more than 25 years of experience in ANN use self-written code when compared to those with less than 25 years of experience in ANN." The second hypothesis used in this paper is as follows: "Researchers with less than 25 years of experience in ANN use some platform to develop their hardware in ANN when compared to those with more than 25 years of experience in ANN."

This study aims at evaluating the use of commercial software and hardware as well as their respective prospects for the development of application areas among the ANN research community. This allows both new and experienced users to profit from the community experience and select the most tested and proved software and hardware alternatives.

The overall organization of the paper is as follows. After the introduction, we present the materials and methods in Sect. 2 used to analyze both hypotheses. Section 3 reports the results of the main findings of the data analysis and discusses them. Finally, in Sect. 4, we present the conclusions of the paper.

2 Materials and methods

This section defines the materials and a method used in this study and includes the experimental procedure, sample, and statistical analysis. The experimental procedure reports all the interventions made to carry out the questionnaire. The sample describes the participants and their characterization. Finally, the statistical analysis defines all the materials and methods used for the data analysis.

2.1 Experimental procedure

To evaluate the use of the commercial software and hardware solutions, a survey was prepared and submitted to the ANN international community.

For this questionnaire, a knowledge discovery approach was taken. A few hypotheses were presented at the very beginning, such as to verify whether the commercial tools that are well known are in fact used more often than any other tool, but the knowledge discovery approach was used to extract the most important conclusions instead of simply verifying previously set hypothesis.

Since a survey questionnaire cannot be easily repeated, it must be carefully prepared. Figure 1 depicts the implemented strategy through a block diagram.

The first step consists in structuring the survey according to the objectives, resources, and population. Before presenting the survey, an informatics platform should be implemented and tested.

In the data collection stage, it must be ensured that the data are correctly collected and that the platform chosen performs well in collecting and presenting the data. This is closely related to the next block diagram that refers to access to data. If an informatics platform is used, data collection and access to Data are done in the same interface.

Data analysis was done to prepare this paper using circular graphs and logistic regression (LR) to test both of our hypotheses.

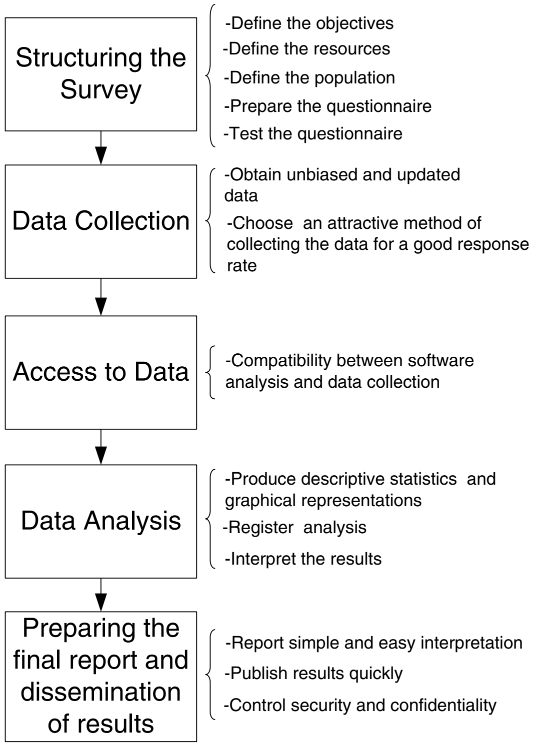

Fig. 1 Block diagram representing the steps taken to implement the survey questionnaire [18]

The survey questionnaire was composed of five parts. The first section characterizes the population (categorical variables). The next two sections collect the software and hardware information, and the last section verifies in which areas the ANN will be used more often in the future. In total, the questionnaire was composed of 14 questions.

The survey was presented to the ANN international community through a Web site, and the invitation was sent through e-mail and the most common mailing lists of the ANN community.

2.2 Sample

The sample consists of the group of people who chose to respond to the online survey. Since the sample is selected based on potential participants own action, the type of non-probability sampling method that is used is the self-selecting sample. The obtained data are made up of 155 samples.

Group A includes researchers with more than 25 years of experience in ANN, and Group B includes researchers with less than 25 years of experience in ANN.

2.3 Statistical analysis

The free online survey was constructed by using the Google Forms tool. Data were statistically analyzed with IBM® SPSS® Statistic software.

In a questionnaire, besides reading the direct values of the answers, it is possible to analyze the underlying relationships between, in this case, the population and their answers. To do so, in this work, LR [19, 20] is used. Through LR, it is possible to verify which variables best explain the output. Equation 1 shows the logistic function.

The variable z, which is the input of the logistic function, represents the exposure to a set of independent variables, while $f(z)$ represents the probability of a particular outcome, given that set of explanatory variables.

$$f(z) = \frac{e^z}{e^z + 1} \tag{1}$$

The variable z, usually defined as shown in Eq. 2, is a measure of the total contribution of all the independent variables used in the linear model.

$$z = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k \tag{2}$$

Once the coefficients of the linear regression model are obtained, they are used to describe the size of the contribution of that risk factor. The coefficient is known as odds ratio and can be written as exp(b). The interpretation of exp(b) is as an estimate of the odds ratio between the two related variables. A positive value of the regression coefficient signifies that the explanatory variable increases the probability of the outcome, while a negative value of the regression coefficient means that the variable decreases the probability of that outcome. A large regression coefficient indicates that the risk factor has a strong influence in the probability of that outcome, while a near-zero regression coefficient means that the risk factor has little influence on the probability of that outcome [21].

In order to achieve the results, the LR algorithm initially takes into account all independent variables of Eq. 2. The LR algorithm is iterative, so at every step, it deletes some of the variables that do not have any significant relationship with the output. At the end, the LR algorithm leaves only the significant independent variables that have some relationship with z. Sometimes, a z variable that does not have any significant relationship with the independent variables in the equation may occur. In this case, the conclusion is that there is no relationship between the z variable and the independent variables in the equation. In this study, only the significant relationships are presented.

In statistics, a result is called "statistically significant" if it is unlikely to have occurred by chance. More specifically, the significance of a test is the maximum probability of accidentally rejecting a true null hypothesis (a decision known as Type I error reject the null hypothesis when it is true). For each presented result, the significance value is presented. The significance value used in this paper was the $p < 0.05$, which indicates a significant value.

3 Results and analysis

3.1 Characteristics of the sample

Figure 2 shows the age distribution of the sample. The largest quota of the sample lies between the 30 and 40 years age range, though globally it is quite well spread.

Figure 2 resumes the highest academic degree of the sample. Figure 3 shows that the vast majority of the sample has doctoral studies and almost 50 % of the sample has post-doctoral studies.

Figure 4 shows the number of years of involvement in research with ANN.

The areas for which the researchers developed work are represented in Fig. 5. As can be seen, the two most selected areas are the Engineering and Natural Sciences. It is interesting to note that these areas correspond to the one who developed more ANN, Engineering, and the one that inspired ANN, that is Natural Sciences.

3.2 Additional information

In this section, the focus was placed in knowing the software and hardware preferences of the ANN community.

In Fig. 6, it is possible to see the information about the software used more frequently.

Figure 6 shows that Matlab and self-written code take the largest share of choice. There is also a large share of other software being used. This share is distributed in the following way:

Neuron and Python (3 %), Mathematica, PyBrain, Nest and Brian (2 %), Lens, PDP, Weka, NNPred, NeuroSolution, LVQPAK, SOM Toolbox, NNSYSID, Torch, GENESIS, Topographica, Oger, NetLab, AMORE, NEAT, MAPLE and libSVM (1 %).

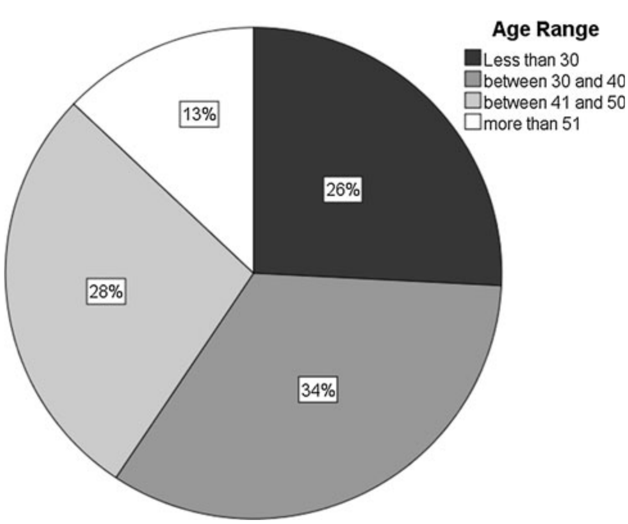

Fig. 2 Age distribution of the sample

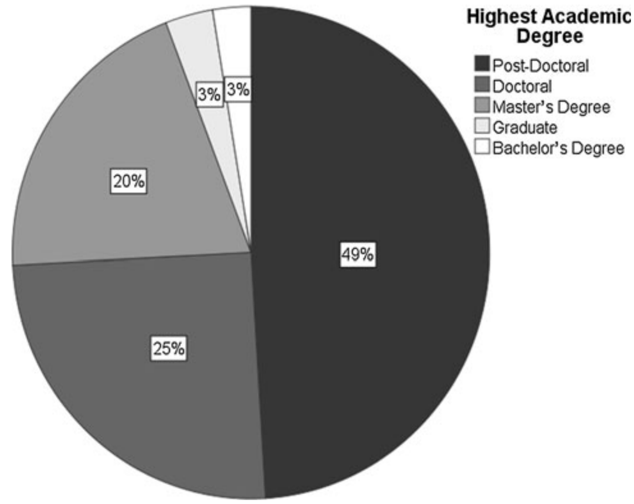

Fig. 3 Highest academic degree of the survey sample

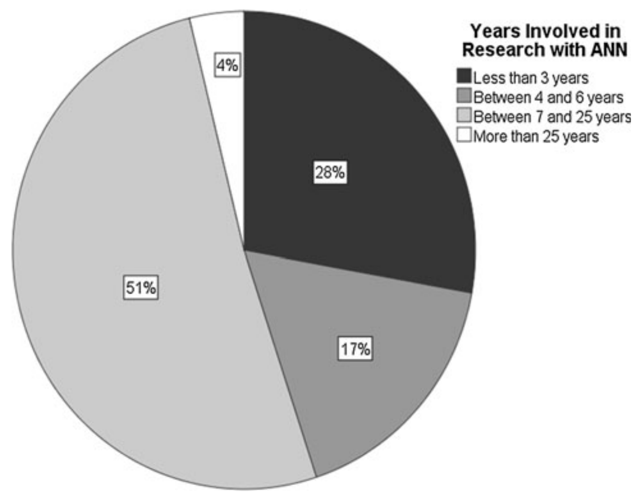

Fig. 4 Number of years involved in ANN research

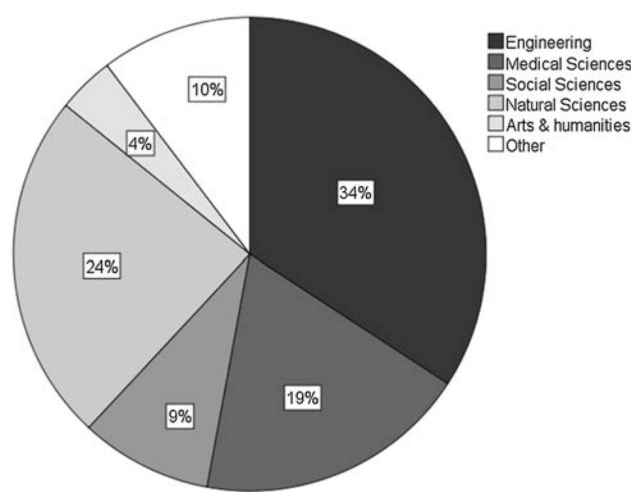

Fig. 5 Areas for previous developed work with ANN

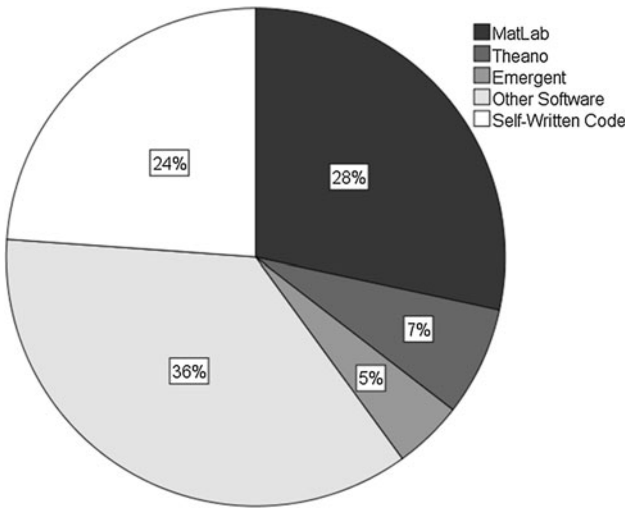

Fig. 6 Software used more frequently among the ANN community

The reasons pointed out for choosing MatLab are as follows: complete software, open-source, powerful and fast processing, easy programming, flexibility, and availability of different neural network models. After MatLab, it is possible to find that Theano (7 %) and Emergent (5 %) are the most used software. This is due to its simplicity and speed of usage, and only in Theano case, the facility to use the group processing units (GPU). It can also be stated that the use of self-written code is to answer specific research questions, such as study novel types of neural networks which are not available in the commercial software packages.

The questionnaire also inquired about the use of other software in the community. The answers are presented in Fig. 7 and have a very large value for other software. Among the answer for this question, it is possible to find the following tools: SNNS, Weka and PLearn (5 %), R package and Lens (4 %), Brain, Python and NetLab (3 %), GENESIS, Brian and SOMPAK (2 %), Oger, SPSS, NNtolkit, Nest, Neuron, pybrain, NNSYSID, Neuron, Nest and Joone (1 %).

From Fig. 7, it is possible to observe that the most used second choice software is Matlab (19 %) followed by Neuron and PDP/PDP++ (both with 6 %).

Other questions in this section are in regard to the software that best meets the needs of the ANN community. The results are presented in Fig. 8.

For the last question in this section, it is possible to find that the community evaluates self-written code (34 %), Matlab (29 %), Emergent (5 %) and Brian (3 %) as the solutions that best meet their needs.

To understand the necessity of using specific hardware and which hardware was chosen, four questions were placed in the questionnaire. A resume of the answers obtained is depicted in Table 2.

Figure 9 shows very interesting and somehow surprising results. The commercial hardware used by the researchers includes ASIC, in a total of 23 %, while the remaining 77 % of the answers is composed of general purpose hardware: graphics processing units (GPU) and NVIDIA (a graphics processor manufacturer). These solutions are used simply as a hardware accelerator.

Figure 10 refers to the platforms used by the researchers to develop their hardware. FPGAs are the preferred choice (50 %), followed closely by ASICs (45 %). The remaining answer refers to an implementation based in very large-scale integration circuits.

The prediction of application areas with larger growth in ANN can be seen in Fig. 11. According to the researchers' opinion, the areas that hold the best promise of future

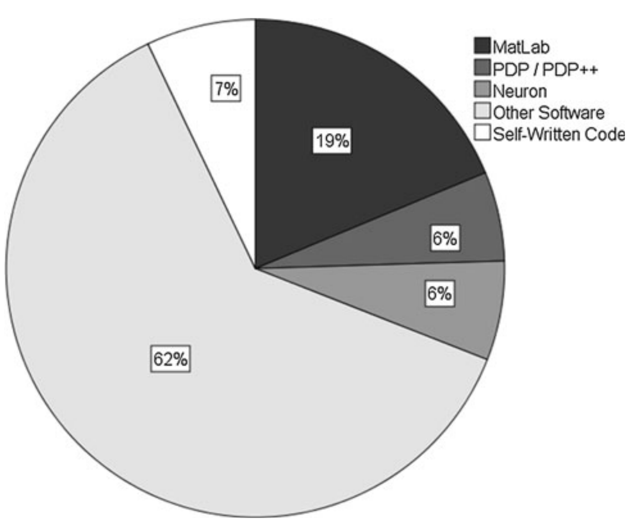

Fig. 7 Other software also used among the ANN community

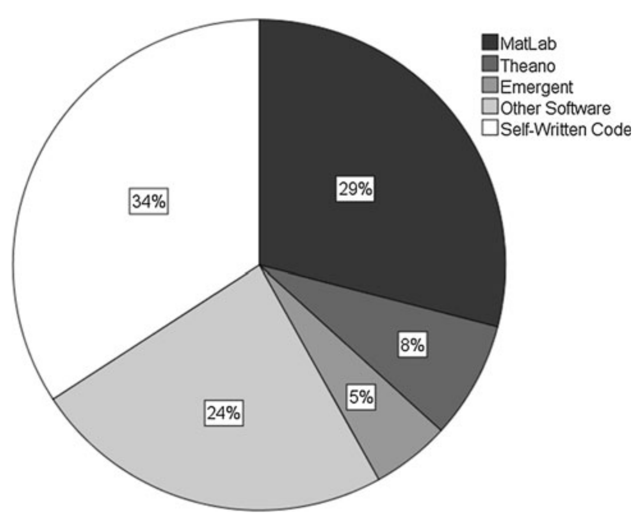

Fig. 8 Software that best meets the needs of the ANN community

Table 2 Resume of the answers regarding specific hardware use for ANN

Hardware for ANN	Yes		No	
	Freq.	%	Freq.	%
Q1—Need for specific hardware for ANN	61	39	90	58
Q2—Used commercial hardware for ANN,	32	21	119	77
Q3—Developed hardware for ANN	15	10	135	87
Q4—Utility of a toolbox for fast hardware implementation of ANN	88	57	52	34

development for ANN are: Engineering and Medical Sciences. Natural Sciences will still have an important role.

3.3 Verification of the hypothesis

The aim of this section is to test both of our hypotheses using the LR test and discover if the null research hypotheses are retained or rejected.

3.3.1 Hypothesis 1

Table 3 presents the LR test results

According to Table 3, the null hypothesis is retained since the significant value is higher than 0.05; in other words, there is no significant difference between the two groups. Therefore, the researchers with less than 25 years of experience in ANN do not present a significant difference relatively to the researchers with more than 25 years of experience in ANN, when related to the development of their own software tool (Sig. = 0.796, Exp(B) = 1.333).

3.3.2 Hypothesis 2

Table 4 presents the LR test results.

According to Table 4, the null hypothesis is retained since the significant value is higher than 0.05; in other words, there is no significant difference between the two groups. Therefore, the researchers with less than 25 years of experience in ANN do not present a significant difference relatively to the researchers with more than 25 years of experience in ANN, when related to the development hardware (Sig. = 0.549, Exp(B) = 1.971).

3.4 Verification of homogeneity

Since both null hypotheses were retained, we decided to analyze the reason for this fact. To analyze the reason of the retained null hypotheses, we verify the group homogeneity in between-subject designs, which analyses the relationship between the different groups of research experience in ANN (more and less than 25 years) and the

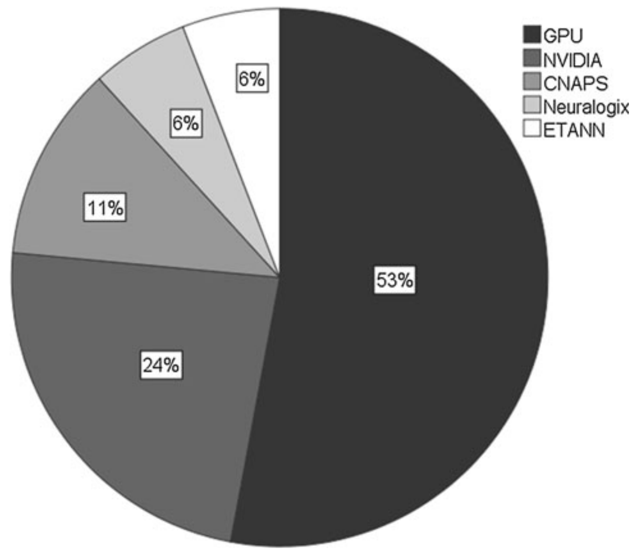

Fig. 9 Commercial hardware used to implement ANN

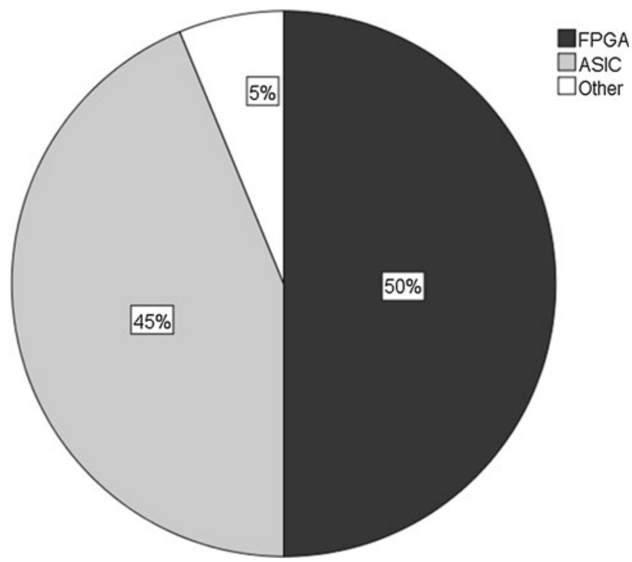

Fig. 10 Platforms used to develop hardware for ANN

categorical variables (age range, highest academic degree, areas where developed ANN).

Table 5 shows the results of the chi-square test and verifies the homogeneity.

There was not a significant effect between the groups and areas where ANN was developed in ($\chi^2 = 7.50$, $p > 0.05$). The effect size was small ($\varphi = 0.222$). Consequently, there is homogeneity between groups and areas where ANN was developed in.

There was a highly significant effect between the groups and age range ($\chi^2 = 28.92$, $p < 0.05$), between the groups and highest academic degree ($\chi^2 = 25.70$, $p < 0.05$) and between the groups and years of experience in ANN

($\chi^2 = 155$, $p < 0.05$). The effect size was medium in both ($\varphi = 0.432$, $\varphi = 0.407$ and $\varphi = 0.1$, respectively). Consequently, there is no homogeneity between groups and these categorical variables. As a result of this, in each categorical variable, we verified that there are biases in the groups. If there is a categorical variable that represents no homogeneity between groups and the respective categorical variable, then it is essential to do the LR analysis to the categorical variable in question.

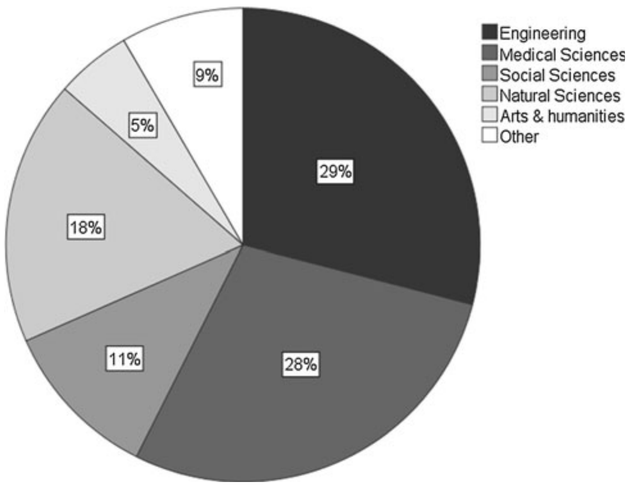

Fig. 11 The prediction of application areas with larger growth in ANN

3.5 Analysis LR to no homogeneity categorical variables

The following statistical tests aid at finding the relationship between the categorical variables (age range and highest academic degree) and the software and hardware. Only these categorical variables were tested because they do not present homogeneity.

To analyze the results of the LR test, toward the categorical variables regarding the development of their own software tool, we cannot assume anything because we do not get any significance value lower than 0.05.

To analyze the results of the LR test, toward the categorical variables regarding the development of hardware, we cannot assume anything because we do not get any significance value lower than 0.05.

Table 3 LR test results

		B	S.E.	Wald	*df*	Sig.	Exp(B)	95 % C.I. for Exp(B)	
								Lower	Upper
Step 1	Less than 25(1)	0.288	1.113	0.067	1	0.769	1.333	0.150	11.821
	Constant	1.322	0.199	44.136	1	0.000	3.750		
Step 2	Constant	1.322	0.196	46.307	1	0.000	3.788		

Table 4 LR test results

		B	S.E.	Wald	*df*	Sig.	Exp(B)	95 % C.I. for Exp(B)	
								Lower	Upper
Step 1	Less than 25(1)	0.679	1.131	0.360	1	0.548	1.971	0.215	18.085
	Constant	−2.288	0.280	66.550	1	0.000	0.101		
Step 2	Constant	−2.255	0.271	69.021	1	0.000	0.105		

Table 5 Group homogeneity in between-subjects design

Categorical variables	Chi-square tests		Homogeneity	φ	Effect size
	χ^2	p			
Age range	28.92	0.000	No	0.432	Medium effect
Highest academic degree	25.70	0.000	No	0.407	Medium effect
Areas where developed ANN	7.50	0.186	Yes	0.222	Small effect
Years of experience in ANN	155	0.000	No	1.0	Large effect

4 Conclusions

The first research hypothesis was stated as: "Researchers with more than 25 years of experience in ANN use self-written code when compared to the researchers with less than 25 years of experience in ANN." The second hypothesis used is: "Researchers with less than 25 years of experience in ANN use some platform to develop their hardware in ANN when compared to the researchers with more than 25 years of experience in ANN."

The null hypothesis was retained for the first hypothesis. This indicates that the researchers with more than 25 years of experience in ANN tend to choose commercial software rather than developing their own, even though they started their career developing their own software. A possible explanation for this is the fact that commercial software offers the researcher the possibility to test their research a fast, efficient, simple way since the commercial software provides most of the algorithms needed to test ANN research saving the researcher time and all the work that goes into developing the algorithms.

The null hypothesis was also retained for the second hypothesis. This indicates that researchers with less than 25 years of experience may not have the skills to work with hardware and adapt it to ANN research or they just do not have the necessity of using hardware and usually stick to the software usage and do not move on to the hardware development.

We verified that there is homogeneity of one categorical variable (areas where the researchers previously developed ANN applications) and no homogeneity (bias) was verified in age, highest academic degree, and years of experience in ANN. For this reason, the LR analysis was done with these latter categorical variables. In these tests, we cannot draw any conclusions because we do not get any significance value lower than 0.05.

In addition to what has already been written, this paper also concludes that:

- The ANN community is well distributed in the age slots and is still growing with a large share of new researchers and a smaller slot of researchers that are over 51 years.
- 73 % of the sample that answered the questionnaire holds a PhD.
- Self-written code and Matlab are the software solutions that best meet the needs of the researchers in ANN, and in the inverse positions, Matlab and self-written code are the most used software solutions.
- The application area with more implementations developed is engineering.
- About 39 % of the ANN researchers felt the need of specific hardware for implementing their networks.
- About 21 % used commercial hardware for ANN.
- About 10 % developed new hardware for ANN.
- FPGAs is the most used platform when developing new hardware solutions, followed closely by ASICs.
- The majority of the researchers feel that a toolbox for fast implementation of ANN in hardware would be useful.

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